"The roar which the Maypu made as it rushed over the great rounded fragments was like that of the sea. Amidst the din of rushing waters, the noise from the stones as they rattled one over another was most distinctly audible even from a distance. This rattling noise, night and day, may be heard along the whole course of the torrent. The sound spoke eloquently to the geologist: the thousands and thousands of stones, which, striking against each other, made the one dull uniform sound, were hurrying in one direction. It was like thinking on time, where the minute that now glides past is irrecoverable. So it was with these stones. The ocean is their eternity, and each note of that wild music told of one more step towards their destiny."

Charles Darwin, 18th March 1835, on crossing the Andes from Santiago to Mendoza, in The Journal of the Voyage of the Beagle.

THE MORPHOLOGICAL, SEDIMENTARY AND HYDRAULIC PROPERTIES OF TWO COARSE CLASTIC (PEBBLE) BEACHES ALONG THE HERITAGE COAST OF GLAMORGAN, WALES.

N.E. CALDWELL

A thesis submitted for the degree of Doctor of Philosophy.

CNAA-Polytechnic of Wales, April 1983.

Certification of Research

This is to certify that except where specific reference is made, the work described in this thesis is the result of the investigation of the candidate.

Candidate ...Neil E. Caldwell...

Director of Studies ...A T Williams...

This is to certify that neither this thesis, nor any part of it has been presented or is currently submitted in candidature for any degree at any other University or Polytechnic.

VOLUME 1

TEXT

The morphological, sedimentary and hydraulic properties of two coarse clastic (pebble) beaches along the Heritage Coast of Glamorgan, Wales.

N.E. CALDWELL

ABSTRACT

This thesis attempts to clarify those morphological, sedimentary and hydraulic properties which typify coarse clastic beaches.

A tracer study on a low energy beach at Gileston identified shape and size sorting processes. Results showed that particle thickness (C-axis) was the most susceptible parameter to swash/backwash processes, and that tracers possessing relatively larger C-axes travelled relatively further along and down-beach from the injection point. An analysis of the relationship between tracers and the background beach population showed dissimilarity between (1) 'returned tracer populations' and the original population of tracers, and (2) individual tracers on the beach surface, and material with which they were in contact (their 'host populations'). A modified model of sediment deposition beneath sea waves has been proposed.

A number of refinements, which have successfully classified pebble beach morphology, have been made to a model originally devised for a micro-tidal sand beach environment. As a result, the crucial importance of swash berm development and its location, to the identification of different depositional environments, and hence sedimentary structures, has been recognised.

A sedimentological study comprising granulometric data from 37,080 beach particles confirmed the existence of a basic zonational shape structure on both Gileston beach, and a high energy beach at Nash. Statistical evidence and size/shape distributions were used to quantify along and down-beach sediment structure on each beach. However, an original model's preference for use of the B-axis in size/shape analysis seems to have led to an incorrect rejection of particle mass (size) as a factor determining the transportational and depositional potential of a particle. In this thesis the identification of several pertinent sub-facies arrangements specific to each beach, has led to the conclusion that the influence of particle size on sorting is predominant when energy conditions are high, whereas shape factors predominate when energy conditions are low.

Two new proto-type swash force transducers, each based on different physical principles, were built and field tested to provide direct swash zone wave data. Considerable developmental problems were incurred, but although swash velocity and flow pressure data were only consistent enough for a qualitative appraisal of results, the basis for a more thorough-going investigation of swash zone phase relations and entrainment pressures has been established. Future research objectives in this field have been identified.

PREFACE AND ACKNOWLEDGEMENTS

This research was undertaken during a five year period when I was employed at the Polytechnic of Wales either as a Research Assistant (1978-1981) or on various Manpower Services Commission employment schemes (1977 and 1982). During the course of this time an important development took place which assisted the objectives of my work. A strong link was forged between the Polytechnic's Science Department and the Glamorgan Heritage Coast Joint Management and Advisory Project, an environmental conservation project dedicated to the protection of a large proportion of the beautiful coastline between Barry and Porthcawl (see Fig: 1.1).

The project officer, Dr John Howden, made every effort to encourage the growth of scientific research into all aspects of the coastal environment. This led to the establishment of a Coastal Research Unit in the Science Department of the Polytechnic, which incorporated research projects covering the geomorphological, geological and botanical sciences, as well as aspects of civil engineering. This thesis represents the first of these projects to reach completion, and I am pleased to know that a copy will be lodged as one of a series of future reports in the library of the Heritage Coast's Southerndown Field Centre.

Whatever the nature of its findings, this thesis reflects a massive quantitative undertaking involving the utilisation of considerable logistical and financial resources. In this regard, I would like to acknowledge the generous support provided over the years by the Welsh Office for many aspects of the work of the Coastal Research Unit. In particular, this enabled me to develop the swash transducer work which forms Chapter 7 of this thesis.

But foremost among the 'external' funding agencies has been the Manpower Services Commission who established several employment schemes during the period of research. These not only enabled the collection of a quantity of data which would otherwise have been impossible, but provided the chance for many young people to receive a useful work experience which included contact with some of the technical facilities offered by the Polytechnic. As a result, many of the participants either obtained further employment or were stimulated to return to their studies.

In total, 40 or more MSC sponsored individuals made some useful contribution to this research. They enabled me to proceed on true Baconian principles, which preclude any premature speculation through the employment of 'unlettered underlings'. But, although Bacon arrogantly believed that it was "....somewhat beneath the dignity of an undertaking like mine that I should spend my own time in a matter which is open to almost every man's industry." (1), I was always more than prepared to get my own hands dirty! Particular thanks is due to the following: Pamela Stockwell, David Watkins, Janet Norman-Phillips, John Davies, Paul Inson and Keith Abbott.

It is with pleasure that I acknowledge the financial and practical support offered to me by the Polytechnic of Wales, in particular in terms of the Research Assistantship which I received. Certain Departments and individuals deserve special mention. The technical and administrative staff of the Science Department played a key supportive role which was much appreciated. Dr Guto Roberts collaborated unselfishly and enthusiastically on the swash transducer work, despite continual set-backs and disappointments.

Elsewhere in the Polytechnic, Dr Tony Yule and Mr Roger Scott, of the Maths and Computer Science Department, kindly provided advice on computer graphics and the choice of statistics, respectively. The whole staff of the Computer Centre were extremely helpful at all times, and especially when the most unreasonable requests were made. Viv Cole and Malcolm Coundley, of the Media Resources Unit, made efforts beyond the call of duty in producing the vast amount of photographic and reprographic material which is incorporated in Volume 2 of this thesis. Finally, the technical staff of the Department of Civil Engineering aided the design and construction of field equipment, and in so doing, provided one more sign of the interdepartmental co-operation which is such a vital aspect of research work.

There were advantages and disadvantages in finding myself working in a Science rather than a Geography Department, which are worth noting. It brought me into contact with the pure sciences and encouraged me at all times to base experimental work upon an objective methodology. It prevented me from making some of the cruder assumptions associated with my discipline. Furthermore, the work on swash force transducers arose from a direct synthesis between geomorphological and applied physics research, which was wholly positive. On the other hand, the absence of a Cartographic or Graphics Department was a considerable draw-back. It meant that I had to design, draw and annotate almost all the diagrams presented in Volume 2, often with the aid of the computer. I also wrote the vast majority of computer programs, with the occasional assistance of the Computer Centre staff.

Two respected research contributors to the field of pebble beach sedimentation, Dr A.P. Carr (of the Institute of Oceanographic Sciences, Taunton) and Dr J.D. Orford (of Queen's University, Belfast) willingly discussed ideas on the work with me on many occasions, enabling me to formulate a relevant plan of research. Their encouragement is gratefully acknowledged, although I take full responsibility for the results and conclusions presented in this thesis which may differ in certain respects from those previously proposed by the above investigators.

Very special thanks is offered to my Supervisor, Dr A.T. Williams (and Oscar) for several reasons. Not only has he been responsible for transforming my latent interest in coastal processes into a genuine enthusiasm for the fascinations of sea and beach, which could last a lifetime, but, in his unselfish concern for my practical (as well as academic) needs, he has engendered in me a respect for him which will most certainly last as long. The advice which Dr Williams constantly offered, and the personal contacts and introductions which he made on my behalf, have hopefully added something tangible to the thesis contents which reflects the thanks with which they were received.

In conclusion, I want to acknowledge the considerable debt of gratitude which I owe to Mrs C.J.C. Jones, who played a supportive role throughout this work, and rendered vital assistance at a time when the research was being written up. Her daughter, my wife Betsan, also deserves some special recognition for patiently enduring the restrictions caused by five year's research work, when, in bringing up a young family and continuing to work at the same time, she had to shoulder more than her fair share of the daily burden. No truer words were written than those, oft quoted during the Second World War as well as in our household, which proclaimed:

"They also serve who only stand and wait" !

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(1) Francis Bacon (1620) "The New Organon and Related Writings", edited by F.H. Anderson (1960), Liberal Arts Press, New York.

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LIST OF SYMBOLS

Symbol	Description
A	Long particle axis
B	Intermediate particle axis
C	Short particle axis
ϕ	Phi
β	Beach slope angle
δ	Maximum angle of repose of particulate material
Q	Volume of sediment contained in a subaerial beach profile
S	Beach width
h	Beach height
g	Acceleration caused by gravity
S^2	Sample population variance
y/x	Individual value making up a sample
$\bar{y}/\bar{x}$	Mean values of a sample
m/n	Sample number
H_o	The null hypothesis
P	Probability value
$\leqslant$	Smaller or equal to...
$\geqslant$	Greater or equal to...
$^\circ$	Angular degrees
W_s	Wave steepness criterion
H_o	Deep water wave height
L_o	Deep water wave length
H_b	Breaking wave height
T_b	Breaking wave period
$\bar{H}_3$	Significant wave height (mean of the highest third of waves)
T_o	Deep water wave period
B_s	Breaker steepness criterion
t	Swash period
pd	Phase-difference
l	Swash length
C_x	Swash velocity
ρ_s	Specific weight of a pebble
ρ_w	Specific weight of sea water
C	Capacitance, or Sunamura's (1975) dimensionless discriminant between 'constructive' and 'destructive' depositional condits.

Symbol	Description
$\simeq$	Approximately
k, k' etc	Constants
V_o' V_s	Phasor Quantities

CHAPTER 1

INTRODUCTION

"About thirty years ago there was much talk that geologists ought only to observe and not theorise; and I well remember someone saying that at this rate a man might as well go into a gravel pit and count the pebbles and describe their colours. How odd it is that anyone should not see that all observation should be for or against some view if it is to be of any service."

Charles Darwin, November 29, 1859 (More Letters, 1903, 1:126)

1.1 STUDY OF THE COASTLINE

It was natural for the island people of Britain to take an interest in their coastline, and the processes which affected it, long before the emergence of popular scientific methods. In fact the origins of coastal science in this land can be traced back many centuries (Lyell, 1865). A great deal of early work was based on relict sequencies, with attention being given to the structure of coastal deposits formed in the course of marine transgressions and regressions. Prior to the latter half of the nineteenth century, there were no structured geological methods for the study of the coastal zone, although many descriptive treaties were written outlining the destructive potential of the sea.

By the end of the last century, a large number of papers on particular aspects of coastal morphology, and regional descriptions of many areas of sea coast, had been published by European and American authors (Lamblardie 1789; Palmer, 1834; Mackintosh, 1868; Coode, 1875; Gilbert, 1885; Cornish, 1898a; Richardson, 1902). These were soon followed by fuller syntheses of the gradually accumulating data (Cornish, 1898b; Gulliver, 1899; Richthofen, 1901; Fenneman, 1902; Davies, 1912; Passarge, 1912; Johnson, 1919). Since this time, and particularly following the impetus generated by the practical considerations of the Second World War, there has been a vast proliferation in the quantity and range of coastal investigations. Today, there are many reviews and reference manuals available to the coastal scientist, (Zenkovich, 1967; King, 1972; Davies, 1973, Coates, 1974; Hails and Carr, 1975; Komar, 1976, and the CERC series of technical manuals to name but a few).

The coastal zone is the scene of action of extremely powerful forces, and the processes that take place are exceptionally complex and diverse. Many of man's practical activities in pursuit of his existence, involve him in influencing and responding to the natural coastal environment. The most obvious aspects of this relationship concern the construction and use of ports, and the design of coastal defences. The nearshore area, being marginal territory, has not always been given the attention it deserves. Oceanographers, for instance, have been slow to turn their attention to shallower depths, while geologists and geographers did not initially venture one step beyond the shoreline. For a complete picture of the range of processes that take place along the coastline, it is essential to have a clear conception of the relationship, between (1) the physics by which energy is transformed and water masses are moved in the area of wave action, and (2) the effect that this has on the composition and structure of beach sediments. It is important to appreciate the dual nature of this relationship, since the rearrangement of beach sediments by waves can also have the effect of altering the physical properties of wave action. "It therefore follows that only the union of both aspects of the question, i.e. dynamics and morphology, gives rise to the science." (Zenkovich, 1967, p21).

1.2 NOMENCLATURE

It is important, at the outset, to have a clear set of terms which can be used to define the area of study. Starting with the sediments of the coastal zone, the term 'beach' is given to the accumulation of loose material found around the limit of wave action. It can be one of the most variable landforms, extending from the extreme upper limit of wave action to a position offshore where only the largest waves can cause appreciable movement of the bottom sediments. From a tidal point of view the beach can be divided into backshore, foreshore and nearshore zones (Fig: 1.1A). The backshore is defined as the zone above the limit of normal high spring tide. The foreshore zone represents that part of the beach regularly affected by waves between high and low tide. The nearshore zone is that which extends from the uppermost point always covered by water to a depth at which substantial movement of beach material ceases under normal circumstances.

From a morphological point of view a second set of sub-divisions can be made (Figs: 1.1B and C). A 'berm', 'ridge' or 'step' is a terrace usually formed at the upper limit of the foreshore zone. During the phase between spring and neap tide a series of these ridges may be formed at progressively lower beach face positions, and in many circumstances during the second phase of the spring-neap-spring cycle some lower beach berms may initially persist until they are acted upon by several tides. Another feature is formed under the breakpoint of shoaling waves, known as the 'breakpoint bar'. The term 'bar' implies that the feature is never exposed above high water (although in certain circumstances, as will be seen (Chapter 5), this can happen on pebble beaches). From Figures 1.1B and C it can be adduced that features typical of pebble beaches differ from those found on a sand beach; this difference of character will be referred to many times in the current work.

A third and final set of beach sub-divisions which are of importance arise from the physical properties of the waves. The terms 'shoaling', 'breaker', 'surf' and 'swash' are used to divide up that area between the point at which the orbital motion of waves first interacts with the bottom sediments, and the point of highest wave run-up on the beach face (Fig: 1.2). The shoaling zone lies between the former point and the breaker zone. In this zone the deep-water wave form changes dramatically such that wave crests become higher and more sharply peaked, while troughs become longer and flatter. The increase in orbital velocity of water particles, which is a key feature of shoaling waves, leads to their eventual destruction. A wave will break when the increasing velocity of water at the wave crest exceeds the decreasing velocity of wave form.

Landwards of the breaker zone lies the surf zone in which the now solitary wave forms travel over a relatively shallow bottom towards the shore. Eventually, each wave dissipates its remaining energy (stored in kinetic and potential forms) on the beach face as swash and backwash. Extreme turbulence is formed in this , the swash zone, and there is a high level of sediment entrainment. Because of tidal influences the exact location of these hydraulic zones is continually changing. On steep beaches where waves break relatively close to the shore, the surf zone may be undeveloped.

(A fuller treatment of the hydraulic properties operating in these zones is provided in Chapter 7). For detailed discussion of the physical principles involved see: Stokes, 1847; Munk, 1949; Russell and MacMillan, 1952; Longuet-Higgins, 1953; Barber and Ursell, 1948; Bretschneider and Reid, 1954; Weigel and Fuchs, 1955; King, 1962, 1966; Miller and Zeigler, 1964; Wells, 1967; Galvin, 1968, 1972; Komar and Gaughan, 1972; Gaughan and Komar, 1975).

The work of Schiffman (1965) and Kirk (1973), which will be elaborated upon in Chapter 7, has identified peaks of wave energy dissipation in the breaker and swash zones, with a relative trough occurring across the surf zone. At its simplest level the dynamics of a beach system can be described in terms of three major elements, namely, beach sediments, sea water, and the zone of water and deposit interaction (Dolan 1966). The energy which drives this system comes initially from the wind, and is greatest at the water surface. This energy power-house, driven ultimately by the sun, creates a perpetuating dynamic system in the nearshore zone which, as a result, is one of the most rugged environments on our planet.

1.3 PEBBLE BEACHES

The term 'pebble' will be used throughout this thesis to distinguish beach material in the pebble, cobble and boulder categories of the Wentworth Scale (Table 1), (material greater than 4mm or -2ϕ intermediate axis). The term is not proposed as being superior to any other used to refer to coarse clastic beach material (shingle, gravel, cobble), but is preferred because of subjective satisfaction with its meaning. This is not considered of any great hindrance so long as it enables the reader to distinguish between fine, particulate, sandy material, and coarse collections of stones. Such subjective labels are not relied upon during experimental analysis when exact ordinal measurements are given.

Orford (1978, pi) has pinpointed the popular views of pebble beaches:

> "....to the public eye [they] are for sitting on by holiday makers (at least until the intertidal sand is exposed), they are to be dug up in re-runs of the D-day landings, or when commercial exploitation lends a hand. ....They are driven over to gain better vantage of the sea, and sometimes when the

holiday is over, the vehicle is left behind. They make good filters for cleaning crude oil remnants from the sea, while other recent uses have been the siting of nuclear power stations and gas and oil pipelines. Gravel beaches represent the least cared-for section of the littoral strip and appear to be amongst the best natural dustbins, as they collect and store waste from landward and seaward sources."

Yet, as Orford (1978) points out, they are one of nature's finest answers to the problem of coastal protection, acting as a hydraulically sensitive natural engineering structure to buffer the land from the sea.
Pebble beaches are largely derived from the reworking of conglomeratic material accumulated during the Pleistocene (Davies, 1973). There are two general sources (1) the undermining and exposure of non-indurate glacial or periglacial material forming a cliffed foreland to the present-day beach, or (2) the gathering up of glacially derived material from the continental shelf by the rising post-glacial sea level (Hardy, 1964; Carr and Hails, 1972). This association between glaciation and the distribution of present day pebble beaches is evidenced by the restriction of the majority of these landforms to the mid and northern latitudes (Hayes, 1967). This in turn explains why most interest has been shown by scientists from

countries within those latitudes, who have been more concerned with the geomorphology and dynamics of pebble beaches rather than in comparative studies with relict sequencies.

The main differences between the coastal behaviour of pebble and sand accumulations are related to their different permeabilities, and the resulting variations in mode of sediment transport. Sand is predominantly moved by the sea in suspension and saltation, whereas pebbles are usually transported through sliding and rolling along the bottom. Higher inertial forces in the coarser material restrict its entrainment to higher energy areas of the breaker and swash zones. Since movement is initiated by the high velocity phases of wave action, resulting direction of transport is governed almost exclusively by this process. Sand, on the other hand, can be suspended by both waves and tidal currents, and its direction of transport is a reflection of the resultant of the two forces operating at any one time.

Muir Wood (1970, p1059) has made the comment: "The extensive literature on the engineering properties of a natural beach is principally concerned with fine to medium sand foreshores. In consequence, a number of generalisations have been made concerning the properties of a beach that do not apply, however, to a shingle or even to a coarse sand beach." Miller and Byrne (1966) have shown how particle shape, size and sorting values become more important aspects determining resultant sediment transport in the coarser grades. Despite the relative ease with which these parameters can be measured in pebble size material, considerable problems remain in terms of permeability, entrainment characteristics and the occurrence of polymodal sorting.

1.4 THE FACIES CONCEPT

Frames of reference are needed for the purposes of cross-environmental comparison. In sedimentology this reference unit is termed the 'facies'. The American Geological Institute's dictionary lists no less than five separate entries under this term, but they all contain adjectives which stress the distinctive internal characteristics of a sediment facies, together with distinctive and distinguishing properties separating it from other facies types. A facies therefore represents the concrete, material nature of any difference between sediments or lithologies. The principle problem of such a definition, according to Orford (1978, p55) is: "the criteria by which the definition is applied and the manner in which the criteria are optimised."

In a review of the historical and current usage of the facies concept, Orford (1978, Chapter 1) noted the increasing looseness with which the term has been applied. Orford (1978) returns to Walther (1893-1894), an original proponant of the twin concepts of facies identification and facies modelling to learn that "....from being (existence), we explain becoming (genesis)". Walther (1893-1894) set out the principles upon which facies can be defined, and stated (Vol3, p981) "....every facies is related to other contemporaneous facies and if we want to interpret a fossil deposit, we must compare it with the sediment it is correlated with at the present time." While respecting the simple clarity adopted by Walther, Orford (1978) took issue with his uniformitarian reliance on present day environmental models as a means of explaining all types of relict sequencies. This, he argued, imposes a major contraint on the development of facies models for "....if present day facies constructs are not representative, then explanation of ancient sequencies must become biased, if not spurious." (Orford, 1978, p7).

Selley (1970) provides a useful range of facies attributes, which, though not exhaustive, lists the major parameters. These include particle and mass geometry, lithology, palaeontology, primary sedimentary structures and palaeocurrents. However, the diverse nature of all these attributes illustrates one major difficulty when applying an objective methodology to define facies types, namely, the requirement to stress total aspect by integrating all types of variation despite the non-comparability between their physical properties. This tendency has increased in recent years because of the development of statistical theory and its incorporation into sophisticated computer programs, so that modelling becomes less representative of the concrete reality of field sediment (e.g. the use of 'normal' statistics).

1.5 FACIES ATTRIBUTES FOUND ON PEBBLE BEACHES

The range of potential facies attributes is large if inclusion is made of geophysical and geotechnical properties of sediments. However, using Selley's (1970) list as a basis, an examination can be made of those parameters most useful in deducing sediment behaviour, and therefore facies types, on pebble beaches.

1.5.1 Lithology

Although there are a few examples of hydrodynamic selectivity of differing lithologies recorded on coarse clastic beaches, this attribute is of greatest importance in sand grade material (May, 1973). It has to be remembered, however, that lithology may induce other aspects of a clast's characteristics, such as its size and shape, which may in turn reflect facies differentation (Bluck, 1967).

1.5.2 **Palaeontology**

The high wave energy levels associated with the formation of pebble beaches are responsible for the almost complete destruction of palaeontological evidence. There are examples of beaches of predominantly organic origin (Baines and McLean, 1976), but hydrodynamic selection of remnants is of greater importance than any differentiation of species or genus. Palaeontological evidence may be of crucial importance when examining sediments from sheltered littoral environments, but has little or no value on pebble beaches.

1.5.3 **Primary Sedimentary Structures**

The potential of detailed and accurate information concerning flow-structures of aqueous sediments has improved considerably recently (Greenwood, 1970; Law, 1977). Renewed interest in facies modelling can be related to a greater understanding of primary sedimentary structures as a response to fluid flow variation, which has now developed. Indeed, Orford (1978) has suggested that progress in this field has had the effect of diminishing the importance of other investigative procedures. This again illustrates the predominance of sand beach studies where such flow structures are well developed. On coarse clastic beaches the effect of particle size and sediment permeability severely limit the formation of these features, while the unstable characteristics of the material preclude the identification of that which is found (e.g. limited antidune structures beneath standing waves). This is a most important point, because it forces the investigator of pebble beach behaviour back upon more traditional methods (i.e. textural analysis).

1.5.4 Sediment Geometry

Starting at the lowest scale, the develoment of scanning electron microscopy has opened up the field of sediment micro-morphology. However, the size of pebbly material, which makes it easy to apply shape, size and roundness analysis, has resulted in SEM developments being less significant.

The geometry of individual clasts has always been of fundamental importance to sediment description and facies classification. Whalley (1972) has defined particle geometry in terms of weight, density, size and form (shape). If clastic material is of a homogeneous lithological nature, then because of its constant density, weight is proportional to a combination of lithological particle axes. In most instances it has been particle size and shape that has been used to reflect the depositional nature of a sedimentary environment in terms of the spatial distribution of sediment. There has always been some contention between coastal sedimentologists of the relative importance of particle size and shape in controlling depositional characteristics (Bluck, 1967), and in some respects there was an emphasis in early work on size (Folk and Ward, 1957). A more complete discussion on textural methods will be given in Chapter 3, and the question of size vs shape is examined in Chapter 6.

Bulk properties of sediments can be considered in terms of bulk density, porosity, permeability, sorting and bed roughness. Several, if not all, of these properties are related to the characteristic of particle packing. This is a three dimensional phenomenon involving considerations of depth as well as the two-dimensional beach surface. Coring of sand beach sediments, and even mixed sand and pebble material (Giese, 1966), has been undertaken to examine this property. However, the development of a packing methodology has proved particularly difficult and expensive for exclusively pebbly material (Smalley, 1964). For this reason most textural analysis of coarse clastic beaches has been restricted to a surface 'skin' of a few pebbles' thickness, which is often sedimentologically different from the main bulk of underlying deposits. This is a key restriction to such studies and prompted Orford (1973, p61) to comment: "It is unfortunate that this problem has still to be overcome as porosity as a function of packing is so important in understanding shingle dynamics".

Finally, at the macro-scale there is the geometry of littoral sedimentary bodies, known as the beach profile. Although its importance has been recognised in isolation (Lewis, 1931; Kemp, 1961; King and Barnes, 1964; Sonu and Van Beek, 1971), its use in facies discrimination has been limited until recently (Clifton, 1973; Martini, 1975; Orford, 1977). Because of the relative insignificance of most of the facies attributes listed above, in pebble beach studies (with the exception of individual particle geometry), morphology of the beach sediment envelope assumes a major role in any project to elucidate dominant depositional processes responsible for observed sediment characteristics. It is therefore necessary to set the analysis of beach morphology on a sound quantitative basis as a first step towards fuller textural analysis on coarse clastic beaches.

1.6 FACIES MODELS

Using the concept of facies as a sediment's basic structure, facies models are analytical devices which can be used to reveal physical characteristics of sediment deposition. Without such a methodology there could be no genetic element in sedimentology, and stratigraphy would remain a purely taxonomic procedure lacking any dynamic content. Orford (1978) stressed this two-stage approach in facies modelling. The first stage involves the identification, on some acceptable objective basis, of facies types and their intrinsic linkages, while the second stage concerns those mechanisms responsible for their formation. One underlying difficulty associated with facies modelling is that it necessitates an assumption that each facies type should be neatly monogenetic. On most occasions this is not the case, and any investigation has to establish sequential sediment patterns against a 'noise' caused by relict features which blurs the principle distinctions.

Another aspect of the process of facies modelling is that data on which they are based should reflect a range of facies assemblages, each associated with qualitatively different depositional conditions. The preservation potential of observed deposits is a key factor, and for this to be taken into account data should be comprehensive in both space and time. Van den Berg (1977) has, for instance, cast doubt on the important works of Clifton et al. (1971), and Davidson-Arnott and Greenwood (1976) precisely because data collection was restricted to the summer months of the year. As a result the 'normal' models proposed are without reference to storm wave conditions. Although data associated with these conditions is logistically difficult to obtain, its inclusion in a rigorous model is an essential prerequisite for empirical applicability. This is especially so since most present day coastal environments are influenced by storm wave spectra.

1.6.1 **The Persistence of Facies Attributes**

The question of the relative role of low frequency/high magnitude events has relevance for many areas of geomorphology. The work of Kumar and Sanders (1976) (in the coastal environment) suggests that the old uniformitarian view propounded by Walther (1893-1894) is in need of change. Evidence from nearshore and offshore Pleistocene sequencies has been used to suggest that the marine element of much of the geological column is dominated by storm sequencies. This may be something of a radical proposition in terms of sedimentation sequences to take full account of storm as well as fairweather phases.

Of the methods currently available to ascertain the persistence of certain facies sequencies in the natural environment, all depend upon a probabilistic methodology. Stochastic models are those which allow for some random element to govern the outcome of some process or combination of processes. In contrast, strict deterministic models purport to predict relationships between elements by mathematical functions, and therefore any error in the prediction is associated with measurement inaccuracies alone. Stochastic models (which include those based on Markov Chain Analysis) have been used to effect in stratigraphy. They have been used to identify cyclical depositional sequencies in lithological cores. Concepts of 'memory' and 'inheritance' contained in Markovian techniques are useful ones to apply to the process-response system of a modern beach. Sonu and van Beek (1971) recognised the stochastic function of past and present processes and past profiles (Sonu and Young, 1970; Sonu and James, 1973), and developed their models accordingly.

All systems have inherent control, but the degree of control can vary from the complete control of a determistic system to the indetermination of a system governed by random processes. Davies (1973, p252) classified points along this continuum as pure determinism, partial determinism, incomplete ordering, semi-random. The usefulness of these subjective tags is questionable, but there is little doubt that because the initial particulate arrangement and morphology of a segment of beach will play a vital part in determining the physical effects of largely random, wind generated, wave processes, the beach system can be modelled somewhere along the continuum.

1.7 BLUCK'S (1967) MODEL OF PEBBLE BEACH SEDIMENTATION

1.7.1 Introduction

The first attempt at facies modelling in a coarse clastic, littoral environment was made by Bluck (1967). Bluck based his model on the selective sorting of beach pebbles according to particle shape and sphericity measurements.

During the course of his work he gathered textural data from six beaches located between Sker Point and Nash Point along the coast of Glamorgan (Fig: 1.3). His thesis was based upon the predominance of shape selection processes in the swash zone, as first put forward by Cornish (1898b) from field observations, and experimentally confirmed by Landon (1930).

1.7.2 The Shape-Sorting Mechanism

This process (Fig: 1.4) is based on the proposition that discs, because of their shape, should be most easily suspended by turbulent swash and carried forward by waves. On settling out of the fluid they should orientate themselves so that their plane of maximum projection is perpendicular to the force of gravity and resisting downward motion. They would then come to rest, and in this position of minimum pivotability would least easily be resuspended in the more gradual flow-characteristics of backwash. Spheres, on the other hand, would be difficult to initially suspend (Fig: 1.4), but their high pivotability would make them easy to roll downslope in the backwash. Over time a significant variability by shape would be expected down the slope of the beach face.

It was Coode (1853) who first recorded the occurrence of greater numbers of spherical pebbles at the base of Chesil Beach, while discs were found in greater proportion at the top; although it was left to Cornish (1898b) to offer some explanation for this phenomenon. Since that time the observations of various authors on shape-sorting across the beach have been found in greater agreement with each other than the results of studies regarding longshore sorting (Humbert, 1968). According to Dobkins and Folk (1970), students of pebble shape can be divided into three camps. Some (the 'agnostics') attribute an abundance of discs on some beaches to the presence of foliated rock types which would wear flat in any environment. According to this camp it is pointless to measure pebbles in an attempt to identify differing depositional loci. Others (the 'sorters') believe in the processes put forward by Cornish (1898b) which imply that abrasion does not change the proportion of discs, but shape sorting casts them into easier accessibility. Still other geologists (the 'abraders') believe that swash action develops discs by abrasion, presumably by sliding pebbles rhythmically back and forth on the beach surface.

Stephenson (in Clark et al., 1912, p274) first used flat pebbles as indicators of beach environment. He was joined by Wentworth (1921) who based his initial opinion on data collected from some New England beaches. However Wentworth (1922a) later joined the 'agnostics', concluding that in general the discoidal shape was inherited from anisotropic parent rocks, and that beach abrasion should make them less flat. Most workers today belong to the 'sorters' (Krumbein and Griffith, 1938; Van Andel, Wiggers and Maarleveld, 1954; Ellis, 1962; Bluck, 1967; Humbert, 1968; Orford, 1975; Kuenen, 1964; Flemming, 1964). Nevertheless abrasion was at one time considered the vital mechanism, with major studies by Marshall (1929), Cailleux (1945), Grogan (1945) and Tricart (1951) urging the rejection of Cornish's views on shape selection.

1.7.3 **Principal Features of Bluck's (1967) Model**

Bluck's system envisages that a loose, poorly sorted mass of pebbles is initially thrown up by storm waves into a bank (Lewis, 1931, 1938). Subsequent post-storm wave action is then responsible for shape-selection processes which eventually gives rise to distinct zones of internally homogeneous, and externally heterogeneous material. As a result of these selective mechanisms, and on the basis of shape data, Bluck (1967) recognised that the surface layers of his study beaches could be subdivided into four zones - a large disc zone landward; an imbricate zone on the beach face; an infill zone towards the base of the beach ridge; an outer frame at the base.

1.7.3.1 The Large Disc Zone

This is found on, or near, the crest of beach ridges; i.e. on the landward side of the pebble accumulation. In this material there is an abundance of disc shaped grains in the larger sizes, with spherical and rod shaped fragments being almost entirely confined to the lower size ranges. Since the modal grain size of the sediment is lower than sizes in which there is a high proportion of discs, disc shaped fragments are not the most abundant variety in this zone.

1.7.3.2 The Imbricate Zone

Immediately seaward of the large disc zone are deposits characterised by a high proportion of disc shaped grains in all sizes. The modal grain size of these pebbles coincides with that which contains the highest proportion of discs. Imbrication of the particles is particularly well displayed in these deposits, although imbrication may be seen elsewhere on the beach.

1.7.3.3 The Infill Zone

Seawards of the imbricate zone is a more complex area in which material with a large proportion of spherical and rod shaped grains predominates. This zone normally has a sheet of sand bordering the imbricate zone, over which particles move very rapidly. Bluck (1967) called this the 'sand run'. Pebbles crossing the sand run accumulate on the seaward side to form a narrow band composed of spherical and rod shaped pebbles, where the modal grain size of the deposit is also the size having the highest proportion of either rod or spherical grains. Seaward of this again is an area in which the spherical and rod shaped pebbles are infilling a framework of larger cobbles. According to Bluck (1967), trenching showed that all three deposits described represented stages in the infilling of a cobble frame, although all three deposits may not always be present at any one time.

1.7.3.4 The Outer Frame

On the seaward fringe of the pebble ridge a framework of cobble and boulder sized particles (Wentworth Scale, Table 1) are to be found, in which the size grade with the highest proportion of spherical particles is coincident with the modal grain size of the sediment. This deposit is usually only one or two grains thick, lying on a surface of sand or rock. It is the best sorted deposit on the beach.

1.7.3.5 Origin of the Zones

A key factor in Bluck's (1967) model is the proposition that pebble ridges are built up by storm waves which , in so doing, destroy any recognisable sorting pattern and mix the sediments into a homogeneous matrix of all sizes and shapes. This is the major means of onshore sediment movement. Bluck (1967) stated that under normal sea conditions net landward transport is small, and quoted Kidson and Carr (1959) in support of this observation, despite the fact that their work was concerned with nearshore rather than onshore deposits. Although Bluck (1967, p132) gave one instance of this storm-related onshore transport of material, as a result of which "spherical particles were found blanketing the various zones already established on the beach", he provided no timescale over which he envisaged occurrence of the build-up/break-down process.

Given the build-up of a pebble beach ridge by these mechanisms, Bluck (1967) then proposed its gradual break-down into the four principal zones, as a result of seaward transport of selected shaped particles. Two types of transport were considered active: (1) movement within the beach, and (2) movement on the surface. The former process was considered to be most common in the material underlying the large disc zone. Backwash of waves breaking on the porous frame travels through the pebbles, and its passage combs finer material seaward, the size and shape of which depend upon the size and geometry of the gravel pore space. Material in this upper portion of the beach therefore acts as a sieve on the infiltering particles (Fig: 1.5). According to Bluck (1967), spherical particles, on some beaches, move more quickly through the pores than do other shapes. Large disc zones of these beaches have aprons of spherical pebbles on their seaward margins which are interpreted as having moved through the cobble frame of the large disc zone.

The nature of surface transport is closely allied to the ideas first proposed by Cornish (1898b). In traction, spherical and rod shaped particles tend to move faster than discoidal ones (Kumbein, 1942); discs have a lower pivotability than rod and spherical particles (Sheppard and Young, 1961; Kuenen, 1964). According to Bluck (1967, p132), "....on all beaches studied, spherical and rod shaped particles are transported seaward by the backwash and accumulate on the seaward fringe of the gravel bar." Thus, in this model, sorting takes place down-beach of the ridge crest, and involves spherical and rod shaped particles being winnowed out of a framework of disc and blade shaped grains. As the former shapes are brought to the ridge base they begin to infill an outer cobble frame of material, which, because of its size remains in situ during both build-up and break-down of the pebble beach. The juxtaposition of larger cobbles and infill material in no way implies their simultaneous deposition (Plumley, 1948; Potter, 1955), since cobbles of the outer frame were present on the seaward fringe before finer grained material arrived.

Bluck (1967, p133) laid great stress on the relationship between the modal size with the greatest proportion of discs and the modal size of the sediment at any point:

"There is a seaward decline in the size grade which has the highest proportion of disc shaped pebbles. The modal grain size of the gravel is smaller than that size with the highest proportion of discs on the landward bar margin, and greater than the modal size with the highest proportion of discs on the seaward bar fringes. Both modal grain size of the gravel and the size grade with the highest proportion of discs are coincident in the sediments of the imbricate zone, which is situated somewhere between the two other locations. These features concerning the disc shaped particles are common to all beaches."

During beach break-down there are two overall functional zones existant according to Bluck (1967). The first is an upper beach zone of erosion, where steady removal of spherical and rod shaped grains is responsible for the formation of two types of lag deposit (the large disc zone and imbricate zone). The second is a zone of deposition in which transported spherical and rod shaped particles are infilling a permanent framework of spherical cobbles (the infill zone and outer frame). What distinguishes the two lag deposits is the degree of reworking they receive from waves. Because the imbricate zone is nearer the sea, it is subjected to more intensive current action. As spherical and rod shaped particles are continually moving seaward and discs tending to lag, reworking by the sea means that a state of equilibrium is rapidly approached when the grain size of the sediment is coincident with that size having the greatest proportion of discs. It therefore follows that deposits of the large disc zone have not yet reached a condition of equilibrium and are reservoirs of spherical and rod shaped grains potentially capable of rapid seaward transport.

1.7.3.6 Classification of Pebble Beach Sedimentation

On the basis of his observations, Bluck (1967) proposed a two-type classification based on incident wave energy. The 'Sker' type facies assemblage is generated by the processes described above, from a ridge of unsorted pebbly material mixed with sand and granules which is positioned around the high tide mark. A thin open framework of spherical cobbles lies to the seaward. After reworking, the four zones become fairly well established with development of lag and infill sub-facies. There is a continual sieving of smaller spherical and rod shaped particles through the open framework of lag sediments. The imbricate zone becomes well developed with a fairly short, asymptotic profile and a seaward decline in disc size. To seaward is the sand run, a thin strip of spherical and rod shaped pebbles and an area where infilling is taking place.

Following creation of these zones, further modification is apparent by growth of the large disc zone. The residuum of discs increases in proportion to the total range of particle shapes, but seaward extension is affected by migration of discs out over the infill zone, or even as a component of frame infill. This extension of the imbricate zone begins to hinder rapid seaward transport of spherical and rod shaped grains over the beach face. Beneath the surface, however, spherical cobbles and large pebbles are released from a reservoir underlying the lag sediments and move seaward to extend the outer cobble frame, or add another outer frame above the already existing zone.

Bluck (1967) provides a model succession for the Sker type facies assemblage which is shown in Figure 1.6A. Bluck (1967) indicated that sub-facies 1 and 2 of this model had been observed during trenching on one beach, whereas sub-facies 3 was hypothetical and based on evidence from some marine gravels related to an earlier sea level (Bluck, 1965). On the basis of the relict succession, Bluck (1967) suggested that there was evidence on contemporary beaches of a gradual landward ridge transgression, presumably associated with post-glacial sea level rise.

Bluck's (1967) second facies assemblage is called the 'Newton' type. This arises from the same initial storm-generated homogeneous pebbly mass already mentioned. It is similar to the 'Sker' type in having the same stages of breakdown, but because it is found in a lower wave energy environment, and mixed with a greater proportion of sand, there are some key differences. The presence of a veneer of sand across the foreshore zone means that the outer frame is either absent or only poorly developed. Instead of just one imbricate zone and one area of spherical and rod pebble accumulation, there are up to three, each corresponding to the late stages of development of this sub-facies. Bluck's (1967) model succession for the 'Newton' type (Fig: 1.6B) is also hypothetical in that it assumes no landward migration of material during beach breakdown. In contrast to the Sker type, the Newton type succession shows an increase in the size of spherical and rod shaped fragments upwards.

1.8 ORFORD'S (1978) MODEL OF PEBBLE BEACH SEDIMENTATION

Orford (1973, 1975, 1977, 1978), working on Llanrhystyd beach, West Wales (Fig: 1.7), tested Bluck's (1967) thesis on pebble beach sedimentation, and proposed a modified version with some important new features. In this work Orford (1978) was also concerned with a reappraisal of textural methods and facies modelling, some details of which will be reviewed in Chapter 3. Evidence from Llanrhystyd enabled Orford (1978) to confirm the existence of Bluck's (1967) basic zonational model, although he identified differences in terms of the spatial and temporal extent of pebble beach facies, as well as in terms of their genesis. Major differences with Bluck's (1967) model are listed below:

1.8.1 **The Role of Storm Events**

It has already been noted that valid facies models need to be based upon a full range of environmental conditions prevailing across the sediment unit. According to Orford (1978), Bluck (1967) failed to identify a specific facies sequence for storm conditions, asserting that storms are responsible for throwing sediment landwards into a chaotically arranged ridge of material at around the high tide swash limit. Orford (1978, p20) took issue with the implication that storm waves do not have the capacity to sort material, and that landward transport of particles predominates under these conditions:

> "Bluck's total incorporation of all material into a swash ridge under storm conditions is obviously not the same as the down-combing conditions experienced at Llanrhystyd under storm conditions. The movement of material up-beach in storm conditions requires an event of some magnitude for which a facies sequence has not yet been recorded."

In Orford's (1978) opinion, Bluck's (1967) two-type classification was only part of the complete picture. In this case, Sker and Newton type assemblages refer only to post-storm/fairweather conditions (Table 1.2). The difference between observed Llanrhystyd storm sequences and that envisaged by Bluck (1967) for storm induced build-up of the beach ridge, appeared so great to Orford, that it indicated a qualitative distinction between the scale of storms and the beach system's spatial stability. Given the distinction between dominantly gravel and mixed sand and gravel beaches, there are no less than eight facies types upon which any complete model of pebble beach sedimentation needs to be built (Orford, 1978).

1.8.2 **The Role of Sand in the Sequence**

Although Bluck (1967) proposed his two sedimentation types on the basis of differing littoral zone energy levels, the role of sand in different sequences was not fully established (Fig: 1.6A and B). Contrast between Sker and Newton types, argued Orford (1978), was induced by the proportion of sand in the beach system as a function of beach geomorphology and level of wave exposure, rather than a contrast induced by variation of the same sediment structure under different wave energy conditions.

1.8.3 **The Distinction between Post-storm Swell and**

Fairweather Conditions

Orford's (1978) evidence strongly suggested that there was some justification for recognition of a fairweather facies assemblage as distinct from that created by post-storm swell conditions. Key to this modification was the analytical power provided by an examination of beach profiles; an aspect largely ignored by Bluck. Using profile configuration as a discriminant between differing depositional environments (see Chapter 5), Orford (1978) was able to observe the rearrangement of sediments in relation to beach morphology. Distinction between post-storm swell, and fairweather conditions was essentially based upon the spatial extent of certain sub-facies on the lower beach.

1.8.4 The Importance of Onshore as well as Offshore Sediment Transport

The issue raised in 1.8.3 above also involved reconsideration of the mechanism of beach ridge break-down as proposed by Bluck (1967). According to Orford (1978), certain types of facies assemblage (linked to profile morphology) depend on onshore movement of selected particles winnowed from lower beach infill zones. This type of depositional process was completely unrecognised by Bluck (1967) whose only reference to onshore transport was associated with storm induced beach ridge build-up. Orford (1978) asserted that sorting processes could operate in both the onshore and offshore directions under different littoral conditions.

1.8.5 The Influence of Profile Morphology

Of all the modifications made by Orford (1978) to Bluck's (1967) original thesis, the inclusion of profile morphology as a key element in facies discrimination, was the most profound. Bluck (1969) appeared to pay little attention to dynamic mechanisms associated with wave processes responsible for sorting action, and concentrated on elucidating a facies model from the arrangement of sediments alone. Zenkovich (1967, p21, and quoted at the end of section 1.1) warned against the tendency to divorce description from the dynamic factors responsible for features being described. This theme was also taken up strongly by Orford (1978) through his insistence on the distinct but complementary roles played by facies identification and facies dynamics. In this context it is interesting to note that in a rare reference to work on the genesis of pebble beach ridges (Lewis, 1931), Bluck (1967) assumed corroborative evidence of his theory of storm related beach ridge build-up. Yet Lewis (1931) actually stated that constructional processes were associated with beach build-up, while destructional storm wave processes were responsible for a down-combing (offshore) transport of sediment.

By including beach profile in an analysis of facies dynamics, Orford (1978) was able to shed more light on factors responsible for facies sequencies identified through statistical procedures. Although he was unable to establish any statistically proven basis for so doing, he divided recorded beach configurations into three types - 'step', 'bar', and 'composite'. While the nature of these profile types and their relation to prevailing wave conditions is elaborated upon more fully in Chapter 5, it is sufficient to note that each was associated with a distinct arrangement of sub-facies derived by wave processes sorting material in offshore and/or onshore directions.

1.8.6 The Sedimentation Timescale

Orford (1978, p410) perceived from his results that, despite differences in facies assemblages associated with profile type, and therefore wave type, "....the basic relation of sub-facies on all profiles does not radically differ." He recognised that there was limited potential for disappearence and re-emergence of sub-facies types since the clear inter-tidal boundary at the ridge base precluded any significant offshore transport of sediment, and there was relatively little storage space within the ridge.

It was Orford's (1978) opinion that sediment differentiation was taking place on two scales. On a daily basis, differing profile-related assemblages were superimposed on a basic facies set, the stability of which indicated long-term genesis associated with the gradual evolution of Llanrhystyd gravel beach. Referring to Beerbower's (1964) work on facies change in alluvial sediments, Orford (1978) noted the geological distinction between allocyclic and autocyclic control of sedimentary processes. The former term distinguishes variation related to major geological disturbances and discontinuities that cause gross changes to a depositional environment. These changes may be caused by climatic, isostatic, eustatic or tectonic activity which manifest facies variation in both morphological and sedimentary characteristics. If these allocyclic factors could be held constant, then all that activity remaining would result from autocyclic control (i.e. constant cyclic activity such as tidal change).

Being a somewhat mechanistic classification system, it has proved difficult to differentiate between results of the two types of control (Schwarzacher, 1964), and this suggests that in most cases control of a sedimentary system is a function of both. Nevertheless, this concept of control at two levels enabled Orford (1978) to examine facies realisations at Llanrhystyd in terms of processes on a time-scale continuum from daily variation in small scale waves, to medium scale tidal and superimposed wave action, to an extreme event of combined storm and tidal surge (Orford, 1977), and finally to an extreme scale of change as occurred during the Tertiary and Pleistocene Periods.

1.8.7 **Spatial Variation in Facies Type**

A final and significant modification of the Bluck (1967) model made by Orford (1973) concerned the spatial dimension of beach processes. Orford (1973) found strong evidence of the concurrent development of Sker and Newton type facies assemblages on different areas of beach. This could have been due to the spatial variance of initial beach structure in terms of sand content (see 1.8.2), and/or along-beach energy variation caused by beach aspect or wave refraction. The existence or absence of a source of fresh material could also influence local spatial facies variation, and was cited by Orford (1973) as a key reason for the succession observed by Bluck (1967) on Newton beach.

1.8.8 **Principal Features of Orford's (1978) Model**

Orford (1973) outlined the beginnings of a revised model which was more fully developed by him in 1978. While recognising the significance of Bluck's (1967) contribution to facies modelling, Orford's (1973) observations at Llanrhystyd caused him to conclude, "The final underlying need of Bluck's thesis is due to his lack of specific process conditions.", and that, "On this basis Bluck's thesis is considered inadequate." (Orford, 1973, p267). Using eight comprehensive sediment samples collected over a 12 month period, Orford (1973) was able to obtain information about the sediment response from a variety of littoral conditions. In so doing, he was not only able to identify Bluck's (1967) Newton and Sker type assemblages, which he equated with fairweather and post-swell conditions respectively, but added a third assemblage associated with storm wave down-combing of the beach ridge. He stressed the role of sand in influencing facies response, and identified the spatial juxtaposition of two facies assemblages on one beach, associated with variance in energy levels alongshore.

After further sampling and the development of a sophisticated package of statistical routines based on Information Theory, Orford (1978) proposed a complete facies model for Llanrhystyd beach. His methodology enabled him to identify five main facies and 11 sub-facies associated with them. He listed the main roles of each sub-facies in terms of predominant beach position and genetic role (Fig: 1.8).

1.<u>Sub-facies 1i</u> This is congruent with Bluck's large disc zone and is located around, and behind the beach ridge crest.

2.<u>Sub-facies 1ii/2i</u> Consisting of medium discs and blades, they form the bulk of upper beach, swash limit constructional berms. They are a spatially mobile facies, especially sub-facies 2i under down-combing.

3.<u>Sub-facies 2ii/2iii</u> These form a reservoir of sediment at the centre and lower parts of the beach. They tend to persist on all profile types, although 2ii is prone to burial by 2i under down-combing.

4.<u>Sub-facies 2iv/facies 4</u> These represent Bluck's (1967) infill and outer frame zones, with 2iv as potential infill for 4. They are most clearly seen under constructional wave action, when 4 is spatially extended by the up-beach winnowing of 2iv.

5.<u>Facies 5</u> This consists of highly equant, fine to medium sized sediment appearing as part of the winnowed element of the outer cobble frame. It is rare in occurrence and spatially limited, but sedimentologically distinct enough for separate facies status.

6.<u>Sub-facies 3i/3ii/3iii</u> These are all winnowed elements selected on the basis of size (<30mm). They are spatially most distinct under constructional wave activity when step profiles predominate. Sub-facies 3i results from the downslope backwash winnowing of upper beach berm units, giving this sediment a strong oblate tendency. Sub-facies 3ii/3iii are found exclusively at mid and lower beach positions, often as the sole constituent of small (<0.3m high) berms fringing the landward margin of the outer cobble frame. They both have strong prolate tendencies, and the two sub-facies can only be differentiated on the basis of size.

Those parts of the full model (Table 1.2) observed at Llanrhystyd were based on a subjective three-profile-type division consisting of step, bar and composite configurations. By adapting Information Theory to discriminate the memory potential of an event sequence, Orford (1978) generated empirical tally matrixes using recorded down-beach sub-facies sequences. From these he obtained empirical probability matrices which, by being powered up, could more effectively identify the level of stochastic/deterministic systems control than the more commonly used Markovian Chain Statistics. For each profile type, he examined relevant probability matrices to ascertain the extent to which particular assemblages (or down-beach sequences) could be most significantly associated with them. He concluded that step profiles showed least systems organisations and hence the greatest stochastical potential. Bar profiles, on the other hand, showed a more deterministic attitude, while composite profiles were between step and bar in variation potential.

Poor sedimentation control in step profiles could have been due to a combination of facies evidence from post-storm swell and fairweather conditions. Alternatively, as step profiles are dependent on berm construction, this stochastic variation could have been a reflection of the wide range of beach face positions at which these morphological units could be constructed. This would result in the creation of berms from a variety of sub-facies sediments. Bar profile determinism appeared to be associated with the capacity of down-combing to repeatedly arrange sub-facies into their equilibrium spatial positions, so that down-beach facies sequences had a reduced potential for variation. Composite profiles showed a continuation of constructional swash at the swash limit and gravel edge, linked by mid-beach down-combing structures. Overtopping of the beach ridge may accompany composite profile development as material is transferred over the ridge crest.

Orford (1978) pinpointed three basic aspects which could be used to establish variation between profile sedimentation sequences and hence facies assemblages. The first was the role played by constructive winnowing of infill elements; notably (1) well structured progressive winnowing by size and shape across the whole active beach width from outer cobble frame differentiation to selective constructional berm development, as in step profiles, and (2) break-down of down-combed material covering the outer cobble frame, by selective up-beach winnowing of infill material. This latter aspect is only exhibited in lower beach zones of bar and composite profiles. A second point of profile difference concerned the spatial extent of major sub-facies positions. In Orford's words (1978, p410), "The spatial balance of sub-facies 2i and 2ii, and the morphology of berm development that relates to this balance, is an important basis for step/bar/composite profile difference." The third key aspect was the distinction between onshore and offshore sediment transport. Step profiles are in this sense onshore dominated, while bar profiles show a predominant offshore motion. Composite profiles show an adaption of this latter process in that sediment also moves landwards over the ridge crest.

But despite Orford's (1978) excellent achievement at discriminating between profile related facies assemblages, he was forced to conclude that the beach facies sequence retained an inherent equilibrium upon which these daily profile changes were superimposed. His ultimate conclusion was that Llanrhystyd beach originated from offshore sediments built up into a proto-beach as part of an earlier barrier system. Particle sorting would have been going on throughout the period of initial barrier definition and subsequent onshore migration with post-glacial sea level rise. Essentially the same sorting processes would have been operating as monitored under step, bar and composite profiles today. The integrated outcome of these was the overall beach sediment differentiation recognised by Bluck (1967).

Onshore movement of the barrier system, involving crestal overtopping and landward transfer of sediment, would not necessarily have destroyed macro-sorting as implied by Bluck

(1967) under severe storm conditions. According to Orford (1977, 1978) such events should only materially affect the upper beach zone, by adding material to the beach crest and to the back beach area. Being predominantly large and medium sized discs, this sediment would have tended to enhance rather than destroy the macro-sorting. During this process the outer cobble frame trundled landwards in the wake of the migrating beach ridge. Constant grinding in the outer frame ensured the prolate tendency of material, whilst the rate of ridge migration dictated the amount of material left behind.

Around 1500 B.P., allocyclic control on the beach diminished with stabilisation of sea level. Autocyclic changes triggered by this last allocyclic event are, argued Orford (1978) still in progress today, with particle sorting progressively moving towards its equilibrium structure. Given that Llanrhystyd beach appeared stable enough to require very severe storms before overtopping was possible, and that the net effects of longshore drifting were negligible within the enclosed bay, he concluded, "....it appears probable that the long-term equilibrium facies sequence is very close to realisation." (Orford, 1978, p415). As a result, he felt able to predict that, because step and bar profiles are composed of beach face changes of an entirely ephemeral nature, it is the composite profile which is best able to survive as a preserved facies due to its back beach accretional element.

1.9 SUMMARY

A basic requirement of research into coastal processes, as with other branches of the Geological Sciences, is that it is based on some relevant frame of reference which takes account of the dual role of dynamics and morphology. So far as the study of beach sediments is concerned, this frame of reference is the facies. The dual basis of the analytical approach is provided by facies identification and facies dynamics.

Coarse clastic, or pebble, beaches have generally been ignored as a suitable environment for the development of facies models, with a few notable exceptions. These types of beach are, in many respects, qualitatively different from their sand beach cousins; these differences being related to characteristic hydraulic behavioural properties displayed by small and large particles. The effect in response terms is to reduce the number of defined facies attributes found on pebble beaches, while increasing the relative importance of those that can be observed. Individual particle geometry and sediment envelope geometry are vital parameters for use in pebble beach sedimentation modelling, although their role has diminished in favour of primary sediment structures in sand beach studies.

Bluck (1967) was the first to develop a facies model for pebble beach sedimentation; this being based on particle size/shape data gathered from some South Wales' beaches (one of which is included in this thesis). He proposed a four zone model based on the principles of swash zone shape sorting first proposed by Cornish (1898b). Orford (1978) tested the basic features of Bluck's (1967) work and verified the existence of his zonational structure. However, he took issue with many of the genetic elements of Bluck's (1967) scheme, which had not taken full account of sea wave dynamics. Orford (1978) included this aspect in a revised model by reference to the changing beach profile. He managed to identify a connection between beach morphology and facies assemblage, although not without recognising the ephemeral nature of these changes. His model gave credence to genetic processes operating at two levels, defined as allo-and autocyclic, making the beach at Llanrhystyd an essentially stable landform on which superficial daily changes could be recorded.

Chapter 2

PHYSICAL BACKGROUND

"Daily it is forced home on the mind of the geologist that nothing, not even the wind that blows, is so unstable as the level of the crust of the earth."

Charles Darwin, (on crossing the Andes from Santiago to Mendoza), 18th March 1835: The Journal.

2.1 THE STUDY BEACHES

To further the investigations into pebble beach sedimentation reviewed in the last chapter, two beaches were selected for close examination. Nash and Gileston beaches (Fig: 1.3) lie along the Glamorgan Heritage Coast between Barry and Porthcawl. Each consists of a well established pebble ridge resting on a wide, bare rock platform. These beaches were chosen for the following reasons:

1. Each is built from the same Lias limestone derived from unstable and extensive outcrops forming high cliffs along the coastline. The vast majority of clasts are therefore lithologically homogeneous, which avoids potential complications caused by variable morphological development

and hydraulic behaviour of different rock types.

2. The nearshore topology on both beaches is similar although an offshore sand bank at Nash (Fig: 1.3) does influence the wave regime.

3. To enhance the possibilities of comparison, each beach is set in a physically distinct position. Nash beach is restrained by a high cliff-line, while Gileston beach is unrestrained and free-standing. Evidence from back-beach surface morphology and excavation suggests that this latter beach has reorientated itself to differing littoral conditions in recent history. It is presently positioned seawards of a gully some 50-100m wide.

4. The size range of particles on each beach is generally similar, having a strong modal peak around 10-15cm long axis (see Chapter 6). However, the supply of fresh material is dramatically different on either beach. Cliff falls provide a constant source of material at Nash, whereas Gileston beach depends entirely on longshore drift to maintain its sediment balance.

5. Although both beaches are located in the same physiographic macro-system (i.e. the Bristol Channel), they are subjected to distinctly different wave energy regimes. Nash beach lies at the eastern end of a segment of coastline

from Sker Point to Nash Point. This faces the dominant and prevalent westerly winds and waves (Fig: 1.3). Wave fetch is at a maximum, extending for more than 5000Km (Fig: 2.5). Thus wave energies on this beach are high.
In comparison, Gileston beach lies along a separate segment of the Bristol Channel's northern shore. Here winds and waves commonly travel alongshore, creating conditions for longshore drift. Wave energy levels are lower here than at Nash, as the result of refraction and limited wave fetch (Fig: 1.3).

For these reasons, the two beaches were highly suitable for investigation. They share factors in common, yet differ in important respects. It was considered possible to distinguish littoral processes in operation on both beaches.

2.1.1 **Nash Beach**

Figure 2.1 and Plate 1 show the physical setting of this beach. The headlands of Nash and Monknash Points act as natural groynes on the longshore drift of material. For this reason accumulation of coarse sediment is limited to the centre and southeast of the bay. There is no complete contact between the beach and Nash Point because reflected waves from the headland pushes finely abraded material back to the northwest. The beach becomes steeper and narrower to the southeast; being 40m wide and 7.5m O.D. high at its crest (average) at the centre of the bay, and 30m wide and 8.5m O.D. high (average) at its crest near Nash Point. Longshore drift is clearly to the southeast.

The cliff/platform junction is higher around Nash Point, although the ridge base remains at approximately 1.5m O.D. for most of its length. Softer rocks outcrop in the centre of the bay and marine abrasion has lowered the platform at this point. Vertical cliffs predominate across the bay, rising from 35m in height near the headlands, to over 50m at the centre. Offshore, a prominent sand bank is exposed at low tide. It runs ESE-WNW from a position 1Km due west of Nash Point. It lies at around -3m O.D. at its southeastern end, falling to around -5.5m O.D. further out to sea (Fig: 2.1). Although the dominant southwesterly waves can reach Nash Point virtually unhindered, the sand bank creates an energy shadow across the centre of the bay.

2.1.2 **Gileston Beach**

To the rear of a wide shore platform runs a sinuous pebble ridge (Fig: 2.2 and Plate 2). This stretches unbroken from Breaksea Point in the east, to Summerhouse Point in the west, where it continues as a thin apron of material beneath steep cliffs. At Breaksea Point a protective wall has been built around two thermal power stations. These have been constructed on the site of a once sand covered peninsula.

The weak upper Bucklandi rocks (see section 2.2) of the foreshore are prone to rapid erosion. The beach/platform junction is higher here than at Nash, being around 3.0m O.D.. The absolute dimensions of the beach are smaller than those for Nash beach. Gileston beach is 5m high compared with 7m at Nash. Beach width at Gileston varies between 29-38m. However, there is a similar increase in crest height towards the east of Gileston (7.5m O.D. at its centre, and 8m O.D. near Breaksea Point). It is probable, despite its beach face dimensions, that the beach ridge at Gileston represents a greater total mass of material compared with Nash beach, because it is free-standing, and has back beach dimensions of up to 15m width and 4m height.

The pebble ridge is banked up in front of low-lying land which is liable to winter flooding from the landward side. This gully-like area falls to around 4m O.D. in some central areas, and long pools of water congregate at these locations to drain through the ridge at low tide. Conversely, at periods of exceptionally high tide, sea water can be forced through the pebbles to the rear at a significant rate. It is apparent, from a view of the surrounding countryside, that the cliff-line which outcrops to the west of Summerhouse Point (running virtually unbroken for some 16km to Trwyn y Witch: Fig:1.3), passes inland behind Gileston beach as a low vestigal slope. Therefore arable land, rising gently inland to the rear of the ridge and gully, lies on top of what is probably a mixture of marine and fluvially derived material infilling a once wide, cliff-bound bay.

The problem of drainage from this arable land, causing flooding behind the beach ridge, prompted the farmer (Mr Thomas of Gileston Farm) to take remedial action on several occasions during the author's investigation of this beach. This enabled a closer inspection of the sub-surface structure of the pebble bank to be made. Initially, the farmer attempted to connect the two largest pools by laying a pipe around 2m depth along the gully. In so doing, the JCB excavator exposed a section, down to approximately 3m O.D., made up of a loose collection of spherical and highly rounded pebbles (between 5-20cm long axis size) bound in a matrix of soil and gravel particles. This was evidence to corroborate a morphological impression that the roots of several fossilised pebble beach ridges extended inland for some distance behind the present day beach.

Then in mid November 1981, Mr Thomas made arrangements for the Welsh Water Authority (WWA) to lay a large diameter (>1m) pipe through the beach ridge to drain the now connected twin pools. His intention was obviously to reclaim the gully area for more productive uses. Starting on the seaward side and infilling at the rear as they went, the WWA drove a trench down to the level of the foreshore platform, through the pebble bank (Plates 3A-F). A schematic reconstruction of the section exposed by this work, is shown in Figure 2.3.

Three major types of sediment could be identified. On the seaward margin of the ridge, large cobbles and boulders formed an unbound tongue extending seawards. This wedge of material was no more than three or four clasts thick to landward, thinning to a single clast at the ridge base. The ridge core comprised relatively large (>10cm short axis), spherical and highly rounded Lias limestone particles. These were firmly set in a matrix of rich brown clayey material, thought to be derived from slow redeposition of suspended clay sediments eroded from clay-rich shales on the foreshore (Grimes, pers. comm. 1981). Much of the water content had been squeezed out of this matrix, making the conglomerate resistant enough to cause problems for the JCB excavator. Lenticles of medium and coarse sand were also found in the sediment. Above this was a capping of currently mobile material, distinguishable by its grey and unconsolidated appearance. Relatively smaller (<10cm short axis), less spherical and less well-rounded pebbles were mixed with granular limestone particles to form a grey slurry in this deposit. The top 30cm formed the contemporary beach surface, and was free from any interparticle infill. This capping sediment was up to 2.5m thick at the beach crest, falling to a thickness of approximately 1m mid beach.

2.2 GEOLOGY

The fullest account of the origin of the Bristol Channel has been written by North (1929). Work by Jones (1930, 1952), Godwin (1934, 1960), Kidson (1964) among others, provide further details of its general evolution. Of more specific interest is work by Hallam (1964) and Wobber (1963, 1967) on Liassic sedimentary structures, Trueman (1920, 1922 and 1930) on Liassic stratigraphy, and Roberts (1966, 1974) on Liassic tectonics along the Glamorgan coastline

In brief, the earliest indications of a major physiographic landform in the area now occupied by the Bristol Channel go back to the Silurian. The stratigraphic record since then is incomplete, with some major discontinuities. Carboniferous and Jurassic (Lias) limestones are well-represented in the sequence. These are covered by Pleistocene and Holocene Sediments. The stratigraphic sequence is shown in Fig: 2.4. It was not until Pliocene times that there was definite evidence of the emerging coastal margin of South Wales. With the onset of glacial conditions in the Pleistocene, sea level fell and South Wales' Ice reached the coast during coldest periods. There is strong evidence found in the existence of exotic beach pebbles, that Irish Sea Ice swept eastwards along the present day coast. It brought with it material derived from western parts of Wales, England and Northern Ireland (Keatch, 1965). Although there have been modifications wrought by Pleistocene Ice and interstadial periods, the development of the region's surface features was completed before this period. Along the coastline, post-glacial history has often been preserved in protected areas, such as Cwm Marcross near Nash Point (Williams et al., 1981).

The Lias limestone rocks, from which the beaches at Gileston and Nash are formed, are highly jointed and faulted. At least five major anticlines and synclines occur between Southerndown and Summerhouse Point (Fig: 1.3). The folds are gentle, open flexures with wavelengths varying from 1 to 2 km, and possessing a very gentle west-south-westerly plunge (Roberts, 1974). Abundant faulting is confined to many narrow fault zones 5-10m wide. Roberts (1974) recognised four major strike trend sets which have all undergone downthrow to produce shear zones and associated jointing. A close correlation generally exists between jointing and faulting, although the two need not be genetically related, since in many cases the faults appear to be later structures.

The vertical sequence in the Lias is one of alternating limestones and shales (dipping gently eastwards and southeastwards). These grade into conglomerate limestones of nearshore facies lying against islands of folded Carboniferous limestone in the west (Southerndown and Ogmore-by-Sea Fig: 1.3). There is much speculation as to the cause of the limestone/shale alternation (Hallam, 1960). Wobber (1967) described four arbritrarily defined field-types of limestone; namely, nodules, nodular limestone, semi-nodular limestone and planar limestone. The depositional structure of these types, and their relation to major jointing and fault patterns, may have some bearing on the production of specific particle shapes and sizes on breakdown, but although ideas exist, firm evidence has yet to be presented (Grimes, pers. comm., 1982).

Near vertical joint planes in the cliffs make material especially prone to marine and sub-aerial attack. Grimes (pers. comm., 1980) has identified a number of different failure patterns associated with particular sedimentation zones and individual strata. The composite nature of material influenced its response to tectonic stress in that flexing was of low amplitude and low frequency. Fracturing, however, was high for the same reason. The effect of ductile shale between brittle limestone led to wholesale fracturing of the harder material. Ductility of the shale produced pronounced meso-structures, the anistropic nature of which provides latent horizontal slip planes. The whole system is inherently unstable and produces much of the dramatic erosion which is characteristic of the coastline.

2.3 TIDES

The only tidal information of any real quantitative value is published annually by the British Transport Docks Board. Statistics are published for Standard and Secondary Ports. Those for Secondary Ports are extrapolations of the former data to an accuracy of 0.5 to 1.0 feet and 20 minutes. There is no Standard Port along the Glamorgan Heritage Coast, and only two Secondary Ports at Barry and Porthcawl. In relatively close proximity are the Standard Ports of Swasnsea and Cardiff, and the Secondary Port of Port Talbot.

Tidal predictions are made assuming average meteorological conditions. When these deviate from the average, errors can be large, especially at high and low water. Wind and barometric pressure can effect tide level. When the wind blows parallel to the shore, long waves can be set up which raise sea level at the crest, and lower it in the trough. However, meteorological conditions are usually relatively constant over a fairly large area, and when two sites are relatively close together (e.g. Nash and Gileston beaches), and in the same arm of the sea, it can be assumed that meteorological conditions are approximately equal at the two sites.

In an examination of shore platforms along the Glamorgan coastline, Trenhaile (1967) took careful note of the tidal regime. Using a simple tide guage devised by Wentworth (1936) a 15 day period of observations was made at Nash and Lavernock Points, every high and low water. Calculated tidal differences at these locations were found to correspond closely with figures obtained through interpolation from tide tables. Given this result (Trenhaile, 1967), and the fact that (for the purposes of the study outlined in this thesis) exact timing or tide height was not critical, interpolated predictions were considered adequate. Of the information available , that for Barry was nearest both beaches. Using linear interpolation, high tide heights at Nash could be expected to range between 4.1m O.D. (neap) to 5.6m O.D. (spring). Those for Gileston should be between 4.3m O.D. (neap) and 5.8m O.D. (spring). Tide times and heights quoted in this thesis are, for simplicity's sake, those for Barry Dock.

2.4 WIND AND WAVES

At any site, the spectrum of surface gravity waves is likely to be made up of components due to locally generated seas and those due to longer period swell waves refracting into the area. Since swell waves may originate well outside any area of interest, and be generated under wind conditions atypical for the area, it is important to distinguish between these two components. The effect of swell trains entering the Bristol Channel from the Atlantic Ocean from a westerly or southwesterly direction is significant. Keatch (1965) reported from 1951 data that more than one swell train per day entered the estuary, and that non-swell days represented only 17% of the annual total. Barber and Ursell (1948) identified swell trains at Land's End which originated from (1) a depression in the North Atlantic, (2) a tropical storm off Florida and (3) a storm off Cape Horn; distances of 1200, 2800 and 6000 miles respectively.

At Nash and Gileston the range of fetch directions is narrower than on a more open coastline. Figures 2.5 and 2.6 provide fetch distances for each beach. However, Heathershaw et al. (1980, p1) point out that it is not sufficient to consider geometric fetch alone because,

> "....the wind transfers energy to the sea over a range of angles up to 45° on either side of the direction in which it is blowing, and thus open ocean fetches are a measure of the wave energy arriving at a point from a similar range of angles 45° either side of the wind. In effect this assumes a fetch of infinite width, whereas on an irregular coastline, or in estuaries, rivers and lakes, the fetch width may limit contributions from the full range of angles."

It is not surprising that as a result of fetch calculations for Swansea Bay, Heathershaw et al. (1980) concluded that its wave climate was dominated by its open fetch to the North Atlantic. Such is also true of the two study beaches.

Wave modification takes place as waves travel further up the Bristol Channel, and at any one time the situation can be extremely complex, with the superimposition of tidal changes and locally generated waves on swell trains. There was no justification for using open-sea wave information to represent wave parameters at coastal sites. Therefore, direct observation was made of such things as breaking wave angle and type operating during fieldwork periods. During more direct investigations of swash processes (Chapter 7) a Rustrak Event Recorder (Plate 4), specially geared for the purpose, was used to obtain periodicity data for computer analysis.

A further source of information was provided by reports of the Department of Energy's "Severn Estuary Wave Climate Study". Four reports have been published (EX 887, EX 914, EX 933 and EX 994) covering wave data from April 1978 to March 1981. This investigation was undertaken as part,of a prefeasibility study for the proposed Severn Estuary Tidal Barrage. The Hydraulics Research Station (HRS) at Wallingford, was commissioned by the DoE to monitor the wave climate at three selected sites (Fig: 2.7). Figures 2.8 A-E, 2.9 A-F and 2.10 A-E show the analogue records from buoys A(A1), B and C respectively. For the three year recording period, overall data retrieval from the Datawell Waverider Buoys was 60%, 92% and 81% respectively.

Reports EX 914 and EX 994 present wind-wave correlations obtained using measured wave data in conjunction with mean hourly wind speeds and directions recorded at Cardiff, Wales Airport (Rhoose), and daily weather reports produced by the Met. Office. Data from Rhoose was considered sufficiently accurate, and no attempt was therefore made to transform values to the estuary. As expected, results showed two predominant wind directions giving the largest waves; (1) westerly winds blowing up the estuary and (2) northeasterly winds blowing down the estuary.

Figure 2.11 shows the yearly occurrence of wind speeds $\geqslant$ 25 and $\geqslant$ 30 knots and demonstrates not only the yearly variability, but also a marked cyclical trend. Three wind roses were published in HRS Report EX 914, and these are shown in Figures 2.12, 2.13 and 2.14. Trenhaile (1967) also used data from Cardiff, Wales Airport for the period 1955-1965, and noted that about 38% of winds blowing over the Glamorgan Coastline were from either the west or the southwest quadrants (202°- 292° true). Johnson (1974) used data from the same source between 1961-1970 to produce a figure of 40% for the same directions.

HRS found that the relationship between wind speed and wave conditions at the three sites was influenced by many factors such as storm duration, variability of wind speed, wind direction, effective fetch length, and the state of the tide. There was however, no indication that very long duration storms (≥6-9 hours) produced significantly higher waves than storms with a duration of between 6-9 hours. This was probably because of the modifying influences of tidal changes. Several storms during 1978/79 showed multiple peaks at the height of the storm. Wind speed and direction was relatively uniform during these periods, but second and subsequent peaks did not significantly exceed the first. A strong tidal effect was evident causing storm peaks around low water for westerly winds, and around high water for northeasterly winds.

Finding that in the absence of wave data, storm generating conditions could be identified from wind data, tide tables and synoptic charts, HRS proceeded to define storm events between 1960-1981, using a lower limit of ten knots to overcome the problem of locating small storms. Tables 2.1 and 2.2 show data sets of U (mean wind speed) for each year, for the two main wind direction ranges 0-90° and 220-320° true, respectively. HRS went on (Report EX 994) to predict return periods for extreme events. For interest these are reproduced in Figures 2.15 A-B.

Finally, Figures 2.16 and 2.17 show two synoptic charts from Report EX 914 which represent examples of meteorological conditions producing significantly stormy events in the Bristol Channel. In the first, a low to the north, with its associated warm and cold fronts, moving west to east, initially produced S-SW winds in the Channel. With the passing of the warm front, winds veered SW-W. After passage of the cold front, winds veered NW. In this case a low to the north and a high to the south interlocked to generate westerly winds and the possibility of long fetch lengths. In the second example (Fig: 2.17) a low over Biscay and Western France, and a high to the west of the British Isles, produced storm force northeasterly winds.

The author also obtained wind speed and direction data from Cardiff, Wales Airport Met. Office. These were in the form of hourly records from November 1977 to December 1981 (covering the whole period of fieldwork). When required, wind roses were compiled from this information.

2.5 SUMMARY

Two well-established pebble beach ridges at Nash and Gileston were selected for detailed investigation. Their physical settings provide scope for controlled comparison, particularly because of the former's cliff-bound, and the latter's free-standing natures. A description of each beach has been provided.

A brief description has been given of the geological background of the Bristol Channel with pertinent references. Consideration has been given to the depositional and tectonic features associated with the Lower Lias sequence. Lias limestone is the major, if not exclusive, constituent of the selected study beaches.

Other aspects of the natural physical setting, including the tidal, wind and wave regimes, have been reviewed. An outline has been given of published sources of quantitative information used in this thesis. Other data was gathered directly by the author himself.

CHAPTER 3

METHODOLOGY

"....the observer can generalise his own observations incomparably better than anyone else."

Charles Darwin, (quoted in 'Darwin and his Critics', Ed. D. L. Hull, Harvard University Press, Massachusetts).

3.1 THE QUANTITATIVE METHOD AND BEACH SEDIMENTS

Wentworth (1919, 1922a, 1922b, 1922c) made the first consistent effort to define quantitative criteria for the description of beach sediments. He was clearly aware of the need to characterise physical properties of particles by some set of parameters which would provide the opportunity of accurate reconstruction at a later date, and yet be capable of easy and reasonably accurate measurment in the field. Wentworth (1919) chose to describe beach pebbles by measurement of three diameters at right angles to each other; the longest (A-axis), the shortest (C-axis) and the intermediate (B-axis), such that $A \gg B \gg C$. However, Wentworth (1922c, p38) was under no illusion as to the difficulty of characterising sediments in this way, and using the resulting measurements in formulae designed to express the general 'roundness' or 'flatness' of a sample:

> "Although the writer has ventured to express the ratios in numerical form, he does not wish to convey any false impression as to their accuracy. He is aware, probably more clearly than the reader, of the extreme complexity of the problem, which involves a large number of unknown factors. The figures given are believed to be within 25 per cent of the truth, and it is hoped they may provoke more accurate and extensive investigation."

Indeed they did.

Much of the work done by sedimentary geologists since this time has been preoccupied with accurate description of sedimentary particles, and in the formulation of shape and roundness indices reflecting certain geometric and hydraulic properties. A second, and complementary area of work has concerned the role of sampling techniques within the framework of statistical theory. Here again Wentworth (1926, p31) made some initial comment:

> "Errors resulting from the geologist's inability to locate the sample properly are probably large. Especially if the sample is taken for the purpose of representation of the typical composition of a deposit, it is likely to fall short of its purpose.

The writer believes that there is a strong tendency in attempting to collect a typical specimen to collect what is more properly known as an ideal specimen."

3.1.1 Sampling Method

A major problem surrounds sampling of materials with non-uniform particle parameters. In this instance, as Cochran (1960, p1) puts it, "....the method by which the sample is obtained is crucial, and the study of the techniques that ensure a trustworthy sample becomes important." Krumbein and Slack (1956) were among the first to review the full range of possible beach sampling techniques, including the six main ones - random or spot, systematic, channel, stratified, cluster, and composite or compound. Most early workers sampled at points systematically located along a linear beach traverse line (Pettijohn and Ridge, 1932). Both Krumbein (1961) and Krumbein and Slack (1956) recommended that various beach zones which lie parallel to the shoreline should be used as separate sampling units. They concluded that for the finer end of the sediment continuum at least, a stratified channel sampling scheme was the best means of obtaining unbiased estimates of mean and standard deviation; a procedure supported by Griffiths and Ondrick (1968).

Orford (1973) noted that although the concept of randomness is statistically desirable, the most efficient response in terms of cost effectiveness often comes from more orthoganalised and systemised frames. Given the variation in sediment characteristics which is often found down the face of a beach, it has become commonplace to take samples along a traverse perpendicular to the shore. This has the advantage of also enabling a record to be taken of the morphology of the beach face. Following Krumbein and Slack (1956), samples can then be taken at equally spaced intervals down the profile; the spacing being dependant upon the number of 'sedimentary units' which it crosses.

This was the procedure adopted by Orford (1978) who established 16 sample points down each profile, with a spacing of 2m. Humbert (1968) departed from this procedure by adjusting the intervals between sampling localities to suit topographic features apparent on the beach. These 'sampling strata' were considered to be: (1) the berm, (2) berm ridges relating to various high water lines, (3) the low water line, and (4) the nearshore bottom. Bluck (1967) initially sampled according to Krumbein (1953) and Krumbein and Miller (1953), "....but once it became apparent that a more zonal arrangement of particle shapes existed on the beach, further sampling was not based on a statistical plan, but rather directed towards those parts of the investigation which would throw more light on the means of particle movement." (Bluck, 1967, p129)

This procedure of zonational sampling is in line with Otto's (1938, p572) concept of the 'sedimentation unit' or, "....that thickness of sediment deposited under essentially constant physical conditions." Although this leaves much to be desired in the sense that "constant physical conditions" could be confined to that process responsible for the sedimentation of one particle only, "....it seems permitted," as Humbert (1968, p6) put it, "to relate the definition to a restricted surface area around the sampling spot." For this reason, Orford (1978) gathered his sample from a 0.25m area centred on the sampling point. The definition also implies that any finer material (granules, sand and mud), which has filled pore spaces after deposition of coarser grades, does not form part of the sedimentation unit. Which part has to be excluded depends on the size sorting of the deposit and may prove to be very subjective (Humbert, 1968).

3.1.2 Sample Size

The question of sample size is also a somewhat subjective matter, dependant upon sediment sorting. Once the objective of a study is known, the most effective design of sampling is that which keeps the number of collected samples as small as possible. Krumbein and Graybill (1965) have called this 'purposeful sampling'. It is obviously difficult to assess before hand what the variation within and between samples will be, and this suggests that a fairly large number of particles need to be measured. But from a pragmatic point of view, "Since the smallest sample size that will sufficiently approximate the material is desired in order to save time (cost), and since an estimate of the necessary size has to be made before starting the fieldwork, these theoretical considerations are of limited value." (Humbert, 1968, p8).

A simple review of the sample number adopted by other workers is pertinent here: Cailleux (1952) used 25 pebbles in the 40 to 60mm size class; Blenk (1960) divided the 20 to 130mm size range into four classes and measured 100 pebbles in each group; Mihailescu (1965) found by trial and error that measuring 120 to 150 individuals in the size classes 40 to 60mm and 30 to 35mm produced 'constant' values of shape and roundness indicies (although Humbert, 1968, considered that only 40 pebbles provided a 'reliable estimate'); Müller (1964) measured 300 pebbles in the size range between 20 and 200mm; Tricart (1965) believed in measuring 50 to 100 particles in the grades 40 to 60mm, 80 to 120mm and 160 to 240mm; Krumbein and Griffiths (1938) used 25 to 50 pebbles depending on the size-form range of the sample; Bluck (1967) measured 50 per size class; Humbert adhered to a minimum of 25 pebbles per ϕ (phi) class size; Carr (1969) sampled a maximum of 500 pebbles at a time; and Orford (1978) used 33 pebbles per sample. The overriding conclusion must be that no one number is superior to any other, accept that the larger the number, the better the representative nature of results deduced from them.

3.2 PARTICLE GEOMETRY

Early work on the representation of sedimentary particles focussed on the measurement of beach pebbles because of the ease with which these could be handled. Subsequent methodologies developed for finer sediments (such as sieving and settling tubes) have now become standardised to such an extent that some of the associated statistical procedures have become inappropriate for pebbly material.

3.2.1 Particle Measurement

Following Wentworth (1919), much discussion has centred around the best means of describing the size and shape of three-dimensional sedimentary particles through linear parameters. The less regular a body becomes, the greater the number of linear dimensions that must be used to describe it. A number of attempts to develop shape indices have used a reference shape against which particles with varying levels of irregularity could be compared (Wadell, 1932 - sphere; Krumbein, 1914 - triaxial elipsoid; Aschenbrenner, 1956 - tetrakaidekahedron). Each of these workers, and others intent on evolving some shape index in a laboratory, have insisted on strict orthogonality between the long (A), short (C) and intermediate (B) axes. This was criticised by both Humbert (1968) and Orford (1973, p63) who stated, "....orthogonal measurements did not always seem indicative of the longest axis." By relaxing orthogonality, both workers found that a faster rate of pebble measurement could be achieved, enhancing sample size.

Because of the popularity of sieving routines (in which the intermediate axis is usually the critical factor), the B-axis has been commonly used to express particle size. Orford (1978) maintained this tradition. However, investigators have found, in using multivariate scatter-grams, that the short (C) axis often contains most information, with the long (A) axis next in importance. The B-axis could usually be omitted with small loss of information (Hulbe, 1957; Biederman, 1959; Griffiths and Smith, 1964). In addition, Carr (1974) has found evidence to suggest that the C-axis is most sensitive to hydraulic processes.

3.2.2 Size vs Shape

There has been some difference of opinion (both explicit and implicit) on the balance of primacy between particle size and shape in determining depositional selection in littoral environments. Carr (1969) and Carr et al. (1970) suggested that shape has no major effect on the depositional characteristics of flint pebbles on Chesil Beach. Bluck

(1967), however, based his sedimentation model on the supremacy of shape selection. While Carr (1969) and others suggest a relationship between average wave energy at the beach face and particle size (such that the highest waves selectively favour relatively larger particles for transport), Bluck (1967) and Orford (1978) assert that, provided a wide range of shapes are available, selection by shape will predominate.

Whether or not shape is the fundamental sedimentary property (Chapter 6) it is undoubtedly difficult to quantify. Theoretically, shape may be considered independant of size, although in practice this is almost impossible to achieve. In contrast with work seeking comparison between irregular particles and some reference object, the work of Krumbein (1942), Corey (1949), McNown and Malaika (1950) and Albertson (1953) has adopted a more empirical approach by examining the relationship between shape and particle settling velocity. Sneed and Folk (1958) reviewed both these approaches. Table 3.1 shows results of their comparison between different shape indices and settling velocities.

Shape also can be represented by plotting two ratios on graph-type diagrams. This has been necessary because, whereas sphericity provides a quantitative value representing the departure of a body from equidimensionality, particles of the same numerical sphericity may have very different ratios between their three axes (i.e. a disc and a rod). The most well known of these procedures is that proposed by Zingg (1935) as modified by Krumbein (1941) (Fig: 3.1). This uses the B/A and C/B axis ratios and has proved an effective discriminatory tool (Blenk, 1960; Rosfelder, 1960; Bluck, 1967).

According to Sneed and Folk (1958), the Zingg Chart has several weaknesses, one of which is the limited number of shape classes (four). Secondly, classes defined by Zingg divide the field of variation very unequally. Sneed and Folk (1958) proposed a new method based on the observation that there are three end-points limiting a system of dimensional variation; namely, a prolate spheroid (with one long axis and two short ones), an oblate spheroid (with two long axes and one short one), or a sphere (with all axes equal). By adopting this trivariant system, their shape diagram became a triangular plot (Fig: 3.2) with 10 shape categories. The difference between the divisions of the Zingg Chart and that of Sneed and Folk (1958), is shown in Figure 3.3.

To complete a suite of particle indexes, Dobkins and Folk (1970) attempted to solve a problem caused by thick discs and thin rods having the same sphericity value, by proposing the Oblate-Prolate Index (OPI). It is based mainly on the value (A-B)/(A-C), which defines whether the intermediate

(B) axis is closer in size to the short (C) or long (A) axis. If B is exactly halfway between, this value is 0.50; therefore by subtracting 0.50 from (A-B)/(A-C), perfect blades have OPI=0.0. All discs, in which B is closer to A, have a negative OPI, and all rods, in which B is closer to C have a positive OPI. However, a disc with the dimensions 10:10:9 is not as significantly oblate as a 10:10:1 disc, and in considering the oblate tendency of a pebble population the latter disc should be weighted more heavily. Similarly, a 10:9:9 rod is not as significantly prolate as a 10:1:1 rod. To take this factor into account, Dobkins and Folk (1970) made the C/A ratio the denominator in the final equation:

$$OPI = 10\frac{\left(\frac{A-B}{A-C} - 0.05\right)}{C/A}$$

thus adding weight to very inequidimensional shapes toward the lower part of the shape triangle (Fig: 3.2).

3.2.3 Particle Roundness

Early attempts at estimating particle roundness were based on visual comparison scales. Mackie (1897) used three roundness classes for sand grains, and Dunn (1911) used ten grades of pebble roundness. Inevitably, it was Wentworth (1919) who developed the first truly quantitative measurement, based on the genetically important idea of measuring the sharpest abradable corner. This diameter had to be divided by some measure of pebble size, and Wentworth (1919) first chose the A-axis, then (1922b) changed to mean pebble radius. Dobkins and Folk (1970) noted that the former measure was adopted by Cailleux (1947) and is still erroneously called the Cailleux Index. They reviewed the main roundness indexes (Fig: 3.4), and compared the accuracy and ease with which each method could be used. Other useful reviews have been made by Heywood (1938), Schneiderhöhn (1954), Koster (1964), Lees (1964), Flemming (1965) and Humbert (1968).

Dobkins and Folk (1970) adopted their own roundness formula, based on the radius of the sharpest developed corner (Wentworth), divided by the largest inscribed circle (Wadell). They called this the Modified Wentworth Roundness, and believed that because it involved direct measurement by holding a silhouette of circles alongside the sharpest corner, it was quick to use, accurate, and less subjective than roundness comparison charts. Humbert (1968 p14) was in agreement on this latter matter, considering roundness charts (such as that assembled by Krumbein, 1941, using Wadell's 1933 formula - Fig: 3.5) created a lack of distinction between well rounded pebbles with fractures, and sub-angular pebbles:

"A pebble with one sharp corner may need as much or

> probably more abrasion to become well rounded than a pebble of equal average roundness with all corners alike. Consequently, if one tries to take into account the distance of transport or the loss in weight involved one does better to measure the sharpest corner only.... than to estimate the overall roundness."

This only serves to illustrate the complexity of objective roundness assessment. Humbert (1968) eventually supported Kuenen's (1956) formula, which itself was a modification of Cailleux (1947). Powers (1953) compared particles with photographs of clay models. Krumbein and Sloss (1963) considered this the best visual method for statistical work, although unequal categories meant that even considerable losses of material by particles in the rounder classes were not marked by change in the roundness value.

Powers' (1953) method displays a weakness which dogs all particle roundness work; namely that it becomes confused with the concept of shape. Although it is generally believed that shape and roundness are independent, this is rarely the case in practice (Rosenfeld and Griffiths, 1953). When estimated values of mean roundness and sphericity are plotted together, the relationship is clear. When operators estimate high roundness, they usually estimate high sphericity as well (Griffiths, 1967). As a result, particle roundness is usually judged to be a less objective measurement than size or shape.

3.3 FIELD METHODOLOGY

Field methodology had to take account of a number of potentially complicating factors. One of these was the irregular topography of the foreshore expressed in the formation of cusps, intermittent berms and ridge crest sinuosity. Orford (1978, p45) made the comment, "Such sediment variations will widen the scope of realised facies, but they only alter the boundary conditions of differing facies rather than invalidate the study." Another problem concerned the variable position of the beach toe, which sometimes became covered by foreshore sand. Orford (1973) considered this a matter of importance to facies modelling, particularly when a regular sampling unit was used along beach cross-sections. However, beach toe positions on Nash and Gileston beaches rarely fluctuated more than ± 1m, and the adopted sampling methodology took proper account of this.

Finally, it was difficult to assess the likely depth of disturbance of surface sediment by waves. Investigations of the phenomenon have been undertaken by King (1951) and Williams (1971) for sandy foreshores. Both investigators established correlations with the average breaker height of incoming waves. King (1951) calculated depth of disturbance to be of the order of 4% of this height, whereas Williams (1971) gave this value as 40%; supporting other work done by Otvos (1965). In general, depth of sediment disturbance on the face of sand or pebble beaches is not easily resolved and makes substantiation of Bluck's (1967) model of sorting by within-beach percolation (section 1.7.3.5) difficult. During the course of a tidal cycle a sand beach may undergo several depositional changes (Strahler, 1964; Williams, 1974, 1975), and there is no reason to believe pebble beaches are any different. However, percolation coefficients of different materials may influence degrees of surface response. Whatever potential differences in disturbance depth may be, there is little doubt that surface sediment on pebble beaches is generally associated with contemporary process conditions.

3.3.1 Principal Methods

It was decided to ally all sediment sampling with traverse lines running parallel to the shoreline. The fixed location of one of these lines is called a cross-section (or section), while a reconstructed configuration of the beach face along such a line (recorded on any date) is called a profile. Cross-sections were fixed by reference to bench marks surveyed into Ordnance Datum at the beach ridge crest and toe. Surveying of cross-sections was undertaken through the use of a Zeiss Automatic Engineer's Level and Staff.

Two sediment sampling routines were adopted; one involving examination of sediments at fixed, regular points down cross-sections, the other using the more subjective approach adopted by Bluck (1967), and Humbert (1968) which directed sampling to features and areas of interest. This latter routine (Fig: 3.6) involved examining sediments at up to six locations; namely, the storm ridge (point A), the contemporary high-tide berm (point B), any breaks of slope or changes in surface fabric noted on the beach face (points C1 and C2), the beach ridge toe (point D) and the foreshore platform (point E). On occasion at Nash, points A and B coincided because of the restrictive nature of the cliff (section 2.1.1), in which case no A sample was gathered. For logistical reasons a maximum of only two C samples were taken, but these generally proved adequate. Sample E was representative of loose material eroded from the beach ridge, but in transit across the platform.

The sediment sample number was set at 30, which was considered the absolute minimum number required to obtain a 'reliable estimate' (Humbert, 1968) of the background beach population. It was not fully adequate on occasion, particularly when polymodal sediments were being sampled, and care was taken when using data for analysis. Pooling of sediment samples drawn from similar spatial and morphological locations enabled populations numbers to be raised to between 150 and 4080 on most occasions (Chapter 6). Sampling was undertaken in most instances by two operators; the one selecting material at 'random' by touching and picking up the particles from the surface beach layer directly behind the point where he or she was sitting, the other recording measurements as they were made. On occasion it was necessary for the sampling operator to make a visual judgement of polymodal sediment distributions, involving boulder-sized clasts, to ensure that the sample approximated the numerical (not volumetric) proportion of each size class. All sampling was therefore done 'on site', whatever the conditions (excepting torrential rainfall), and no material was removed from the beach for later examination.

Each pebble was measured for its long (A), intermediate (B) and short (C) axes using specially constructed sliding calipers (pebbleometers) (Plate 5) capable of measuring material with C-axis $\geq$ 4mm and A-axis $\leq$ 300mm, to the nearest 1mm. For sizes greater than this a tape measure was used to the nearest 5mm or 10mm. The largest A-axis accepted for measurement was 990mm; boulders larger than this were certainly 'permanent' features, and represented less than 0.001% of beach material in numerical terms. Following Humbert (1968) and Orford (1973), strict orthogonality of the three principal axes (Krumbein, 1941) was not maintained, so as to increase sampling speed. Initially, pebble weight was also recorded using spring balances capable of a 0-10Kg range, but since (1) all particles heavier than this were precluded (consistency of measurement being crucial in subsequent computational analysis), (2) sediment was almost entirely Liassic limestone of constant specific gravity (2.2), and (3) spring balances were prone to corrosion in salty sea air and became highly inaccurate, this parameter was soon abandoned.

An estimate of pebble surface roundness was included in some of the experiments, and in this instance the roundness comparison chart proposed by Krumbein (1941) (Fig: 3.5) was used. Most investigators who rely on such charts admit that they are inferior in accuracy to values derived from actual measurements, but are prepared to accept this disadvantage because of the higher sampling speed. Choice of method was also based on the assumption that roundness was subsiduary in its effect on the depositional characteristics of pebbles, in comparison to their size and shape. Its differentiating power is best observed when sorting out either strongly contrasting energy environments, or those intra-environmental sediments in early stages of abrasion (Sneed and Folk, 1958). Only McNown (1953) asserts that differences in surface angularity can make the same shaped particles unstable at varying Reynold's Numbers, which may then affect their fall velocities and therefore their relationshiptosortingmechanisms.

3.3.2 **Major Experiments**

Five main types of experiment were undertaken on one or both beaches, as described below:

1.Experiment 1 The objective was to obtain morphological and sedimentological information from a wide range of positions on both beaches over a relatively long time period, so that beach response for a range of process conditions could be obtained. When this experiment was begun in November 1977 results were intended for use in testing Bluck's (1967) model of pebble beach sedimentation. Orford's (1978) amended model subsequently became available, and the results, although not strictly comparable in form, were also used to examine this version.

Four cross-sections were fixed on each beach, approximately 300m apart (Figs: 5.7 and 5.8), so as to cover a range of micro-environments. Between 10.11.77 and 20.10.78, these eight sections were surveyed and sediments along them sampled at points A, B, C1, C2, D and E. Both beaches were monitored on consecutive days as close as possible after the occurrence of high spring tide, so that a maximum proportion of beach face came under the influence of waves between each survey. This produced 24 sets of samples per cross section, each separated by approximately fortnightly intervals.

Subsequent to 20.10.78, two additional surveys were carried out on Gileston beach, together with four additional surveys on Nash beach. The results form Chapters 5 and 6 of this thesis.

2. Experiment 2 This was run concurrently with Experiment 1, and consisted of tracing movements of marked natural beach pebbles (tracers) from an injection point on Gileston beach. A considerable number of such types of experiment have been carried out on pebble beaches, particularly to identify differing rates of longhore drift for different sizes of sediment. On this occasion an attempt was made to include a wider range of particle parameters than usual in analysis of both longshore and down-beach sorting mechanisms. Monitoring, which involved 12 detailed surveys of the dispersing tracer between 17.3.78 and 23.4.79, also included the first known attempt to examine the relationship between tracers and the background beach population. Results of this experiment form Chapter 4 of this thesis.

3. Experiment 3 This was undertaken in connection with experiment 1, and involved a systematic sampling of beach sediment on a grid system, following the work of Krumbein and Griffiths (1938). One of the difficulties associated with experiment 1, was the fact that cross-sections on each beach were too widely separated to enable a two-dimensional planned reconstruction of the beach face to be made. At the

same time, the subjective sampling scheme biased recordings to certain locations, building a picture which might not be fully representative of the beach face. On four separate occasions (two for each beach) between 24.9.79 and 2.1.80, an approximate 270m x 25m area of beach was divided into a grid with a cell size of 30m x 5m. Sediment samples were examined at the corners of each of the 36 cells, making 50 samples in all. A survey was made of the grid so that it could be reconstructed (Figs: 6.1 and 6.2). Results of these experiments are included in Chapter 6.

4. Experiment 4 This involved systematically surveying the beach face to produce a three-dimensional reconstruction of recorded morphological changes. Another intention was to relate these changes to process conditions on a daily basis. This could only be done indirectly for the results of experiment 1 because of the time-lapse between surveys. On two occasions (one for Gileston between 2.2.80 and 18.2.80, and one for Nash between 18.3.80 and 1.4.80) six temporary cross-sections were fixed around cross-section number 4 on each beach (Figs: 5.7 and 5.8) so that they were approximately 10m apart. They were surveyed daily during a spring-neap-spring tidal cycle. The results are included in Chapter 5.

5. Experiment 5 This consisted of a series of experiments designed to assess the role of swash processes on

sedimentary and morphological aspects of the beach face. Because of logistical restrictions, work was confined to the higher energy wave regime of Nash beach. It consisted of measuring variations in velocity of the leading edge of the swash; recording various periodicities observed in the wave train; and using a specially designed swash force transducer located in the swash zone to record swash and backwash flow pressures. 15 separate experiments were carried out between 1.11.79 and 17.12.81. The results form Chapter 7 of this thesis.

3.3.3 Logistics

More than 130 days (4.5 months) were spent in the field measuring over 40,000 pebbles and 400 beach profiles. Equipment weighing over 1000Kg had to be transported to and from the beach on some occasions. Such a task was only feasible through the use of several Manpower Services Commission employment schemes. As a result, manpower, transport and limited finance became available. More than 40 personnel assisted with fieldwork, although skilled work was restricted to a handful , and, where ever possible, exclusively confined to the author himself.

Ten persons, including the six operators eventually used to measure pebbles in the field, were subjected to a test to ascertain their level of accuracy/error in such work. Each was asked to measure a sample of 30 clasts representing a wide range of sizes, shapes and surface roundnesses. The variance for a set of 10 measurements (for each parameter of each pebble) could be calculated according to the formula:

$$S^2 = \frac{\sum (x - \bar{x})^2}{(n-1)}$$

where x represents an individual value, $\bar{x}$ the sample mean, and n the sample number (i.e. 10). However, the total variance for one parameter, measured 10 times for each of the 30 pebbles could be calculated according to:

$$S^2 = \frac{\sum (x - \bar{x})^2 + \sum (y - \bar{y})^2}{(n-1) + (m-1)}$$

where y represents an individual value, $\bar{y}$ the sample mean, and m the sample number (i.e. 30). For the A-axis s^2 = 0.10206; the B-axis s^2 = 0.14115; and the C-axis s^2 = 0.08040. These gave rise to standard deviations of 0.3195cm, 0.3757cm and 0.2835cm respectively.

By undertaking a simple F-test according to the formula:

$$F = \frac{S_1^2}{S_2^2}$$

the following F values were obtained with two degrees of freedom (270, 270):

(1) $A/C = 1.22$ (2) $A/B = 1.38$ (3) $B/C = 1.76$

These could be compared with F (sig) values of 1.26 and 1.39 for $p \leqslant 0.1$ and $p \leqslant 0.02$ respectively, for a two-tailed test (d.f. = 200, 200). The differences in variance under tests (2) and (3) were then statistically significant.

From this small experiment the following tentative conclusions could be drawn:

1. The B-axis was the most difficult to locate accurately, being least well-defined and open to the widest range of interpretations.
2. The C-axis was the easiest to locate accurately, being well-defined and capable of repetative measurement to within $\pm$ 0.57cm 95% of the time. The capability of the A and B-axes to repetative measurement was $\pm$ 0.63 and $\pm$ 0.75cm respectively for 95% of the time, according to these results.

Additionally, it was noted that the measurements showed a higher range of parameter values for more irregularly shaped, as well as larger particles, which is to be expected. That these conclusions are only tentative is a reflection of the relatively low sample number. It must also be noted that only the variation in the 10 attempts at measuring the same parameter for the same pebble could be examined since no absolute value for each parameter could be obtained. Nevertheless, results showed a pattern which could be understood, and suggested a tolerable level of agreement between operators.

With regard to surface roundness, overall variance was 0.07166, making a standard deviation of 0.8365 roundness units. Therefore operators could categorize to within $\pm$ 0.8 roundness units 95% of the time. Another test during which the operators were asked to categorize 10 silhouettes (each with exact roundness values computed using Wadell's 1933 formula - Fig: 3.4), confirmed this level of error by producing a standard deviation of 0.7642. Results using surface roundness data had obviously to be treated with caution.

3.4 STATISTICAL METHODOLOGY

3.4.1 Choice of Particle Shape Parameters

Modern multivariate techniques have made it tempting to "....gather every explicit variable about a phenomenon without regard for mathematical independence, and then after reduction expect to find uncorrelated themes of variance explanation, which can be given casual status" (Orford, 1973, p59). A more precise choice was made for the purposes of the present investigation. Sneed and Folk's (1958) Maximum Projection Sphericity (MPS) was chosen over its rival (that of Krumbein, 1941) because of its closer correlation with the behavioural properties of settling particles. Dobkins and Folk's (1970) Oblate-Prolate Index (OPI) was also computed.

Despite some of the criticisms levelled at it by Sneed and Folk (1958), Zingg's (1935) shape chart (Zingg Diagram) was given preference over that of the former investigators (Folk Diagram), except for the most detailed analyses. The main reason for this was the Zingg Diagram's simple four-category construction which was easy to understand, and had been used with effect by Bluck (1967). Particle size was initially described by all three principal axes, although results exposed some interesting relationships between size and shape (Chapter 6).

3.4.2 Normal Statistics and the Concept of Sorting

Frequency distributions play a central role in statistical treatment of data, and are used as theoretical models against which observed data can be examined for randomness. Additionally, they formulate the guiding rules of statistical analysis which permits the prediction of sampling distributions of certain statistics, such as the mean and variance, together with the significance testing of results. However a problem has surrounded use of the normal distribution in relation to generally skewed and often polymodal beach sediments.

In 1938, Krumbein argued that there was no _a priori_ reason why any one statistical model should be used in approximating sediment distributions. Middleton (1962) repeated this assertion by insisting that no rational physical model confirming the log-normality of sediments had yet been developed. According to Orford (1978), popular insistence on the use of normal frequency distributions has threatened the very credibility of sediment textural analysis. "Not only is the analytical framework of facies modelling in need of renewal, but sufficiency of the basis of present day analysis also needs examination". (Orford, 1978, p4).

In sedimentology the 'sorting' of some particle parameter is used as a description of the dispersal of observed values around some mean. Udden's (1914) work set the basis upon which sorting has become synonimous with the homogeneity of the depositing medium. From hydraulic considerations, beach sediments tend to lie in the upper flow regime (Froude number > 1), where the to and fro swash movements remove fines out of the nearshore system. Moss (1962, 1963), in two qualitative papers, identified three fundamental populations in water lain deposits:

1. Population A, which comprises an exactingly selected dominant group of particles covering a small size range, although with a widely varying inter-environmental mean particle size.

2. Population B, which occurs in association with A, as an interstitially trapped group. The mean grain size of this population is by definition smaller than that of A.

3. Population C, also occurs in association with A, and sometimes with B. It forms a small proportion of the total sediment and represents the coarsest population.

Sediment sorting is a vital element in facies discrimination. Therefore the way in which this parameter is calculated is of considerable interest. Criticism of the use of standard deviation to distinguish between bimodal, polymodal, highly skewed unimodal and random distributions has been made by Spencer (1963), King (1968), Davis and Erhlich (1970) and Orford (1978). The latter turned to Information Theory as an alternative, although this also has some serious short-comings (Kendal and Stuart, 1961). Epstein (1947) and Mahmoud (1973) have both tried to give validity to the log-normal model, while Folk (1966) supported his own use of normal statistics by suggesting most sediment evidence is robust enough to be interpreted adequately even by inappropriate statistics; something with which Link and Koch (1975) take issue. Graphical methods (Trask, 1932; Inman, 1952; Folk and Ward, 1957 and many others) have also been used as an alternative to product moment measures. Unfortunately, the greatest efficiency comes from the use of every percentile value which suggests their abandonment in favour of moment measures (Folk, 1966).

3.4.3 **Multivariate Statistics**

Lees and Middleton (1967) have stressed the inherently multivariate nature of all geological phenomena associated with process-response systems. Unfortunately, Doornkamp and Mather (1970) consider that a thorough understanding of the theoretical construction and weaknesses of multivariate procedures, while not being essential, is nonetheless a great advantage in guiding their correct use.

The three most commonly used procedures are Factor Analysis (FA), Principle Components Analysis (PCA) and Discriminant Analysis (DA); the latter is used for classifying results of the first two. There has been considerable controversy between the relative merits of FA and PCA (Davies, 1971a, 1971b; Mather, 1971, 1972). Because of the simplicity of the model, most factor processing done by geographers and geologists has been through PCA (Humbert, 1968).

An example of the confusion which surrounds these multivariate routines can be provided. Orford (1973) asserts that FA, unlike PCA, has the advantage of recognising the error term associated with repeated experiment, making the results more reliable. Harris (1975), on the other hand, criticised the most popular procedure for analytic rotation (Kaiser, 1958), which amounts to ignoring any differences among the variables in communality, and tending the structures of FA and PCA towards similarity. Harris (1975, p223) concludes, "It therefore seems compelling to the author that PCA is greatly preferable to FA....The altogether too tempting inference that relationships revealed by FA are more "reliable" than those contained in a PCA of the same data, since the error variance has been "removed" along with all the other non-shared variance, must be strongly resisted. In fact, the opposite is probably closer to the truth."

3.4.4 **Favoured Statistical Approach**

Given these tricky problems of interpretation, the advantages of multivariate statistics were considered minimal. Humbert (1968), for instance, backs up his multivariate results with others obtained by size/frequency analysis. Although Orford (1973) considers this a somewhat tedious approach, he gives credit to Bluck (1967) for effectively using it in facies discrimination. Fortunately, high speed computers and graphics systems now make it possible to present data in pictorial form infinitely faster than it could be achieved by hand. Thus there is a minimal loss of contact between original and hypothetical variables (i.e. a complete picture of sediment sorting can be seen without the loss of information involved in graphical or moment measure characterisation). It was decided, therefore, that the size/shape approach of Bluck (1967) should be adopted in combination with the advantages provided by modern computer technology.

In addition, it was decided that non-parametric statistical tests should be used if at all possible, because beach sediments tend to be skewed (Folk and Ward, 1957). On some occasions the mean and standard deviation have been used to describe sample populations, but this has been done in full cognizance of their weaknesses. They are mainly employed as preliminary pathfinders to further analysis. It was felt that the chosen statistical approach would provide the greatest potential for facies recognition.

3.5 SUMMARY

An explanation of the early attempts at quantitatively characterising sediments has been provided. Some of the problems associated with mathematical expression of particle size, shape and surface roundness have been reviewed. The need for theoretically adequate sampling techniques, which improve the geologist's ability to locate the sample objectively, has also been stressed.

Against this background, the effectiveness of major shape and roundness indices has been examined by reference to published results. Reasons have been given for the choice of shape parameters, as well as such methodological considerations as sample size and sampling procedure. On the basis of these, the adopted field methodology has been presented, alongside some tentative evidence of its potential accuracy. Five key experiments which form the basis of this thesis, have been outlined.

Some of the more important sedimentological considerations of statistical theory have been discussed, with particular reference to problems of the 'normal' distribution. Alternatives to this approach have been presented, together with some justification of their use. Some of the dangers inherent in advanced multivariate statistics have been elaborated, and a favoured statistical methodology proposed in the light of these observations.

CHAPTER 4

TRACER EXPERIMENT

"I had also, during many years, followed a golden rule, namely, that whenever a published fact, a new observation or thought came across me, which was opposed to my general results, to make a memorandum of it without fail and at once; for I had found by experience that such facts and thoughts were more apt to escape from the memory than favourable ones."

Charles Darwin (1859), On the Origin of Species.

4.1 BACKGROUND

The first experiment to determine the movement of material under the action of waves, using marked particles, was carried out by Richardson (1902). He stated (Richardson, 1902, p123) that the experiment "....was carried out by myself in December 1898, after consultation with Dr Vaughan Cornish, who most kindly offered to bear half the expense...". From this inauspicious origin grew a technique which was to become almost standard practice in civil-engineering investigations concerning all sorts of shoreline constructions, during the post Second World War period.

Using brickbats (chosen because of their availability, distinctive construction, and similarity in size, hardness and specific gravity to the natural beach pebbles), Richardson made a number of observations about their movement, under the influence of waves, subsequent to their injection onto the surface of Chesil Beach. He recorded some considerable speeds at which these marked materials (tracers) were dispersed. One piece travelled 574 yards in 28 hours, enabling him to speculate that the whole 18 miles from Bridport Harbour to Portland could be traversed in 54 days. Under storm conditions he considered even higher speeds could be obtained. This was at least some expression of the transportative power existant in the swash zone.

A second important observation concerned the rate of movement of differing sized tracers. It was apparent that larger material, lying amongst a mass of smaller pebbles of uniform size, could be carried along the beach by waves at a very much greater rate than any of the smaller particles. Richardson (1902, p131) put this "....apparently contradictory phenomenon...." down to the fact that "...smaller stones lie in a more compact mass, and even if disturbed, easily settle down again, and the waves move, as it were, over them as over a solid floor without producing much effect....But if a considerably larger stone is placed on them, the waves take hold of it immediately and force it onwards.....". As a result of this observation, and given the differential size variation apparent along Chesil Beach, Richardson concluded that a certain sized particle, placed at the finer sized end of the beach, would (if it were relatively bigger than the surrounding beach material) travel alongshore until it reached a point where it ceased to be larger than the material around it, becoming 'permanently' incorporated within it.

Since this classic study, most published results have tended to confirm, rather than contradict Richardson's work. Carr (1971), Gleason and Hardcastle (1973) (on Chesil Beach), Kidson and Carr (1961) (in Bridgewater Bay) and Jolliffe (1964) (on some beaches in Sussex), all concurred with Richardson's observation that the largest material travelled furthest. However, Carr (1974) stated that it was not clear from the Chesil data "....to what extent the results are influenced by the size of the background sediment ....nor whether the greater movement of larger material is a function of relative or absolute size". On Slapton Beach, similar experiments carried out by Gleason et al. (1975) did not produce this result. Instead, sorting appeared more dependent upon particle shape. In addition, smaller material travelled furthest.

4.2 **FIELDWORK**

It was decided to carry out a tracer experiment to obtain general information about swash zone sorting processes, while a more comprehensive analysis was being undertaken (Experiment 1, section 3.4.2). Although some of the quantities of tracer material used in experiments outlined above (e.g. 17,200 and 12,350 particles on Chesil - Carr, 1974) could not be matched for logistical reasons, a plan was adopted in which the fullest information about size, shape and roundness characteristics of dispersing tracers would be monitored . A pilot study at Nash using 400 marked tracers indicated that the relatively high energy conditions there would only enable a limited period of intense monitoring. This was because of the high dispersal rate of material and the rapid obliteration of tracer markings. As a result, Gileston beach was chosen as the location of this experiment (Fig: 4.1).

Choice of the experiment site was based on its remoteness from areas frequented by visitors (Gileston is not a popular beach from a recreational point of view), and yet its relative accessibility to the monitoring team. Rather than importing alien material, such as was done by Richardson (1902), for use in the experiment, natural indigenous beach pebbles were selected. In order to gather a population of particles for marking, which was in someway numerically representative of the material on the beach, a special method of collection was designed. A cross-section was located down the beach face using a graduated surveyor's tape, and at 0.5m intervals starting at the ridge crest, 66 samples of 30 pebbles were taken according to the sampling method outlined in section 3.4.1. In addition to the 1980 pieces of material gathered in this way, 20 boulders on the lower beach, which were too heavy to transport to the ridge crest with the other material, were marked while in situ. Each of the 2000 selected clasts was measured along its three principal axes (A, B and C), and assigned a visually determined score for surface roundness. These measurements were subsequently used to compute Maximum Projection Sphericity (MPS) and Oblate-Prolate Index (OPI). The frequency distributions of four parameters of the selected tracer population are shown in Figure 4.2. Tracers were marked with hard drying marine paint, which was retouched from time to time during the experiment. For logistical reasons it was not possible to remove them from the beach for oven-baking as prescribed by Kidson and Carr (1962). Nevertheless, the paint coat proved reasonably effective. Even when largely removed by abrasion, that which remained in cracks and crevices enabled tracers to be located by a careful search.

The pile of tracers was deposited (injected) on a swash berm near the ridge crest on 1.3.78 (Plate 6, Fig: 4.3). First indications of dispersal were observed on 10.3.78, when the tide was at high water spring (Plate 7). Drifting was predominantly to the east during the experiment with no incidence of tracer moving to the west of the injection point (Fig: 4.4). Altogether 12 separate surveys were made of the dispersing tracers, the dates of which are given in Table 4.1. The experiment lasted approximately 14 months, during which time the percentage of relocated tracers fell from 29.2% to 2.4% of the original 2000. The average relocated population (called the 'returned population') was 7%, or 140 tracers. Only those tracers lying exposed on the beach surface could be relocated visually, since only by the employment of radio-active (Kidson et al., 1956; Kidson and Carr, 1959) or metallic tracers (Wright et al., 1978) can movement at depth be ascertained.

Despite the fact that many investigators have used a grid system to locate the spatial position of tracer on a beach face (Joliffe, 1964; Carr, 1974), another method, which could map the tracers more accurately, was used. A period was initially set aside (2-3hrs) during which three or more persons marked the position of 'returned' tracer using drift wood and other materials. At the same time, each was given a unique number using an indelible felt-tipped pen (numbers 1-583 were used on the first occasion, 584-708 on the second occasion, etc.). Then a theodolite was set up over the injection point, and the position of individual or clusters of tracers calculated by recording distance readings, according to the positions of upper and lower stadia on an engineer's staff placed alongside the tracers, and noting the angular deflection of the optical line of the instrument from a permanent mark fixed to the corner of a pill-box on the beach ridge, due north of the injection point. Each time a position was recorded, the tracer(s) were remeasured, and reassigned a roundness value, and their unique number recorded (this was usually removed by natural processes between each survey so that it was not possible to monitor the movements of individual tracers). The sequence in which positions were mapped was also noted, so that it was subsequently possible to examine the spatial distribution of tracers in terms of their size, shape and roundness parameters. On a number of occasions it was necessary to move the theodolite to a second or third position to maintain a clear line of site or accuracy. In these cases additional positions were recorded in relation to the injection point by using the same angle and distance procedure described above.

Complicated though this procedure may seem, it could be carried out accurately by three operators during a 4 to 5 hour period. The relative ease with which subsequent calculations could be made on this data made it an advance over the grid recording system. A computer program was written using simple trigonometric principles, which rapidly transformed the angular and distance readings (including those obtained from secondary positions) into X, Y coordinate values using the injection point as the origin.

Distances along an E-W axis were provided as X coordinates, and distances along a N-S axis were provided as Y coordinates. The 12 sets of results were then subjected to the following analysis.

4.3 RESULTS

4.3.1 Analysis of Variance

In order to assess the degree of size and shape sorting apparent in the tracer distribution at any time, the beach face was divided into three 'down-beach' zones (marked A, B and C in Figure 4.5), and 17 'along-beach' sectors (marked 1-17 in Figure 4.5). Whereas the sectors were chosen arbitrarily, at 20m intervals, simply to effect a means of along beach division, the three down-beach zones were selected so that they reflected changes in beach face angle. Zone A was the narrowest, representing the steepest portion of beach just below the ridge crest (up to 20° from the horizontal). The remaining proportion of beach face, which had a more consistent, lower slope (approximately 10° from the horizontal) was divided equally to form zones B and C. The distribution of tracers mapped on each date, was laid over these adopted beach divisions, and a record taken of the zone and sector into which each tracer fell.

The next step was to see if there were any statistical differences between the resulting groups of data. The usual F-test (to assess significant differences in population variances) was inappropriate because the Bartlet Test showed that the assumption of equal within-group variance was not satisfied. In this situation the F-like Statistic (Li, 1964) can be used because it estimates the within-group variances separately. For convenience, the number of populations chosen for within and between-group comparison in this test was three. While the tripartite division by zones satisfied this procedure, it was necessary to pool some of the sectoral populations to produce three overall groups, each of which represented populations of tracers which had moved progressively further away from the injection point.

For each survey of the tracer distribution, four F-like tests were carried out on the three populations produced by either zonal or sectoral division. These four tests were based on the observed distribution of tracers according to their short (C) axis, surface roundness, MPS and OPI. Results are shown in Table 4.2, which indicates those surveys which produced statistically significant differences between the zonal or sectoral populations. The greatest number of instances in which significant differences were found was associated with tests using the short (C) axis parameter, in both divisions by zones and by sectors.

In the case of surface roundness, there were no recorded differences, despite the fact that both Kidson and Carr (1961) and Joliffe (1964) observed spatial variation in the roundness characteristics of particles in their tracer distributions. This apparent contradiction could have been the result of the fact that the above investigators used artificial tracer material with roughened surfaces, alongside naturally smoothed, marked beach pebbles. Therefore the correlations which they observed between the direction and rate of movement displayed by the two tracer types could just as easily have been related to variations in their respective densities, strengths and shapes, as much as to their differing surface roundnesses.

When the test was carried out using MPS, a number of significant results were found using populations created by zonal rather than sectoral division (Table 4.2). Closer examination of these differences showed that in almost all cases they resulted from a distinction between the population of tracers in zone A, and the populations in both zones B and C (Fig: 4.5). This seemed to indicate that tracers with significantly different sphericities were to be found on areas of the beach face lying at different gradients. When OPI was used, almost half the surveys showed differences in along-beach (sectoral) populations, while down-beach (zonal) populations were less dissimilar.

4.3.2 Graphically Displayed Trends

A graphical procedure was devised along the lines of that used by Jolliffe (1964), to test whether the distinctions observed during analysis of variance tests resulted from down and/or along-beach sorting patterns. Using this procedure the tracers' direction and rate of movement might be expected to display some trend which could be related to swash zone hydraulic conditions. The procedure involved dividing the total population of tracers mapped by each survey, into sub-groups. Taking a particular parameter, such as particle short (C) axis, its size/frequency curve was plotted. This was then divided into four areas using the mean and one standard deviation either side of the mean, as boundary limits. Parameter values falling into these four areas under the curve formed four sub-groups of tracers having parameter sub-means which increased from left to right under the curve.

For analysis of along-beach variation, the straightline distances between each tracer in a sub-group and the injection point were calculated and these used to obtain a mean distance (Plate 8). As these distances were significantly different from the original E-W orientated X coordinated values, they were recalculated using trigonometric principles. The mean distance for each sub-group was considered to represent the straightline distance between the injection point and the sub-group's centroid (centre of gravity). Considering an hypothesis that, for example, tracers with relatively larger, short (C) axes travelled relatively further along beach during the experiment, then sub-groups possessing higher sub-group means, should be expected to produce longer centroid distances.

Along-beach distances are plotted, in the case of C-axis, in Figure 4.6A. The results show how the four sub-group centroid distances varied in each of the 12 tracer surveys. This was in fact the only parameter which produced a clear and consistent trend. 11 of the surveys showed sub-groups possessing either the second largest or largest sub-group means produced the largest recorded centroid distances. In many instances, the trend clearly indicated that centroids from sub-groups with increasingly larger means produced progressively longer centroid distances. This pattern began to break-down on the last couple of surveys as the 'returned population' number fell particularly low.

For analysis of down-beach variation, it was necessary to obtain straightline distances travelled up or down the beach face from the relative position of the injection point by each tracer in a sub-group, before using these values to calculate the sub-group's down-beach centroid (Plate 8). This again necessitated recalculation of the N-S orientated

Y coordinates. As the line used to divide the tracers into zones A and B for the purposes of the F-like test described earlier (Fig: 4.5) coincidentally followed this relative position along the beach face, distances travelled above or below this line by each tracer in a sub-group was used to fix the sub-group's centroid. These are plotted in Figure 4.6B according to variations in C-axis size, because this was again the only parameter which showed any consistent trend. It shows that tracers possessing larger than average C-axes generally travelled further than average down the beach face during the experiment. Again, this trend began to break-down in the results of the last survey because of the loss of far-travelled tracers, rather than as a result of any reverse in the direction of movement.

4.3.3 Linear Regression

Ungrouped data was treated by linear regression analysis to identify significant relationships between various particle parameters and the distances travelled by tracers in either along or down-beach directions. A Stepped Multi-Regression Routine (from Western Michigan University Computer Centre's STATPACK Statistical Package) was used to fit regression lines using either along or down-beach distance values as the dependent variable. A regression line was first fitted to the parameter with which the chosen distance values were best correlated. An ordinary F-value was calculated for the population variance, and if this proved significant at $p \leqslant 0.01$, the program selected the next best correlated parameter and combined it with the first to see if a better fit could be obtained for a recalculated regression line. In no case, however, did a combination of parameters ever produce a better fit.

For each survey, Table 4.3 shows the parameter against which a regression line, if any, could be fitted. All six parameters were used in this test.In both along-beach and down-beach directions it was the C-axis which generally enabled the best prediction of distance variation to be made. It was clear from an examination of the distribution of points around each regression line, however, that the fit in both cases was poor (Fig: 4.7). On average, only around 4% of the total distance variation in the tracer distribution could be predicted in either direction using the C-axis values.

4.3.4 Pattern of Tracer Dispersal

A picture of the environmental regime during the experiment was built up using wind speed, deep water wave height and tide level data (see sections 2.3 and 2.4). This data is represented in Figure 4.8, onto which a time scale has been drawn indicating all survey dates. By referring to Figure 4.9, which shows the positions of the 12 overall centroids (plotted from the X,Y coordinates of all tracers on each date), an indication of the relationship between environmental regime and the overall pattern of movement of the tracer distribution was obtained. Five significant shifts in the distribution were detected:

1. Between injection (1.3.78) and Survey 1 (17.3.78).
2. Between Survey 1 and Survey 2 (4.4.78).
3. Between Survey 2 and Survey 3 (21.4.78).
4. Between Survey 3 and Survey 9 (28.11.78).
5. Between Survey 9 and Survey 10 (3.1.79).

It was noticable that between Surveys 3 and 8 little significant movement was detected. The same was considered true of the period between Surveys 10 and 12, for although there was some movement in centroid position, the numbers of tracers located on these occasions were so low that only minor variations in individual tracers gave rise to this movement.

Initial dispersion was effected by the first spring tide of March 1978 (6.4m O.D.). Subsequent dispersion was aided by waves produced by an increase in wind speed ($\geqslant$ 20 knots) recorded during the latter half of the month (Fig: 4.8). There was also a coincidence between spring tide and high deep water waves during the period between Surveys 1 and 3 (where records exist). Between Surveys 3 and 7 wind and wave climates ameliorated, until the beginning of July 1978 when stormier weather returned. There was, however, no significant change in the distribution of tracers, possibly as a result of the coincidence between the occurrence of high deep water waves and only a relatively low spring tide (4.8m).

The period between Surveys 8 and 9 was unavoidably long, and considerable changes had evidently taken place. Three occurrences of stormy weather were observed, two of which coincided with high water springs. There was little wave data between surveys 9 and 12, but wind speeds indicated a variable regime with high winds at times.

4.3.5 Discussion

The tracer experiment showed that some particle parameters were more responsive to swash zone hydraulics than others. Surface roundness, for example, displayed no significant spatial pattern in the tracer distribution. It was particle thickness (C-axis) that proved most responsive, and this supported Carr's (1974, p865) observation that "....the short axis is the most susceptible parameter to swash backwash movement. As such , pebble thickness should be relevant in beach stability." The most likely reason for this is that particles tend to settle out of liquids with their maximum projection surfaces horizontal, resisting downward motion (Krumbein, 1942; Albertson, 1953). As a result, most pebbles should come to rest on the beach surface, at an orientation which presents either their AxC or BxC planes, or any intermediary position between these two, to the initial moment force of the swash or backwash. Of course, the picture is complicated by pebble imbrication and beach slope which may account for some of the scatter in Figure 4.7.

The results certainly showed that tracers possessing larger C-axes travelled further along-beach and down-beach; facts which correspond with the results of previous workers. That the relationship between this parameter and distance travelled is not well expressed in linear terms is probably also a result of the complex relationship between tracers and background material. Field experiments, by their very nature, create difficulties of interpretation because of the complicated interaction of hydraulic and sedimentary parameters, occurrence of rhythmic topography, and depth related factors. Such aspects can be controlled in laboratory modelling experiments (Kellerhals and Bray, 1971), although problems of scale are then introduced. Muir Wood (1970, p1063) takes a pessimistic view of all these matters:

> "With the variations of weather, tide and mobility of a shingle beach profile it is unlikely that any

direct general relationship will be found between longshore energy flux and littoral drift even for the same beach, and no reliable quantitative solution of general applicability is foreseeable, without separation of the many parameters."

The Gileston tracer experiment also showed that a degree of shape sorting was apparent, although this could have been related to the relative contribution of the C-axis in shape equations (MPS and OPI). Comparison between prevailing environmental conditions and the pattern of tracer dispersion, suggested that swash sorting processes affecting background beach material is not continuously significant but takes place spasmodically. A possible sorting model for this beach could be that down-beach selective sorting processes predominate, according to principles outlined in section 1.7.2. The fact that sea waves are only active over the basal portion of the beach during a large period of the spring-neap-spring tidal cycle, means that pebbles in this vicinity are able to make greater progress along the beach during this time. If this is the case, then along-beach sorting (which favours the transport of lower beach located prolate material) would be a secondary response to down-beach sorting (Caldwell, 1982).

4.4 RELATIONSHIP BETWEEN TRACERS AND THE BACKGROUND BEACH MATERIAL

In a review of several tracer experiments, Carr (1974) stressed several complicating factors, one of which was the relationship between tracers and background beach material. Moss (1962,1963) used the term 'traction carpet' to describe that mass of saltating particles forming a disturbed layer of beach or river sediments. According to Moss (1963), processes which occur between particles in this layer give rise to the eventual depositional arrangement of sediments. Bagnold (1968) also applied his theory of 'radiation stress' to forces active within this layer. It was therefore decided that during the course of the tracer experiment described above, an examination would be made of the relationship between tracers and background beach material in the hope that it might clarify the role played by tracers in the traction carpet. There appeared to be no published material available on this subject.

4.4.1 Returned Population Characteristics

The returned populations were initially examined to see if they were representative of the original 2000 tracers. A Chi-square (non-parametric) test was devised in which the frequency distributions of the C-axis, surface roundness, MPS and OPI (Fig: 4.2) were divided up into eight discrete units, such that for each parameter 12.5% of the 2000 tracers (250) fell within the boundaries of each. Naturally, these discrete units were of unequal range. The null hypothesis, H_0, assumed there to be no difference between the distribution of a particular parameter's values in a returned population and that found in the original population. If this were the case, then approximately 12.5% of a returned population's parameter values should be expected to fall into the eight selected discrete units for that parameter. Any significant deviation from this proportion in each unit at $p \leq 0.05$ or $p \leq 0.01$ represented a rejection of H_0, with seven degrees of freedom. (The only exception to this procedure involved division of the distribution of surface roundness values which were themselves discrete data. In this case some pooling of categories was necessary to ensure that expected frequencies did not fall below 5%. Only six discrete units were obtained as a result, each with a unique proportion of the total roundness values observed in the original population of 2000.)

Results of this test, carried out using the four chosen parameters, are shown in Table 4.4. They indicated that there were indeed large differences of the kind referred to previously. Figure 4.10 attempts to illustrate the nature of these differences graphically. Although 12 separate tests were carried out to compare each returned population with the original tracer population, Figure 4.10 shows how the general characteristics of the 12 compare with the original population, and therefore observed frequencies are average values only.

Figure 4.10 shows that the returned populations contained proportionally less particles in the C-axis range 0.9 - 5.9cm, than was present in the original tracer population. It is possible that these sizes were just difficult to locate visually on the beach and consequently were lost from the experiment. However, this size range represented a major proportion of the normal part of the C-axis size/frequency curve in Figure 4.2, which reflected the distribution of the general background beach material. Therefore it seemed as if tracer material similar in thickness to the bulk of the background population was readily incorporated within it. Almost 40% of the 12 returned populations were made up particles with C-axes larger than 7.9cm. These were particles which made up the extreme right-hand tail of the size/frequency curve in Figure 4.2, a fact which casts doubt on the representative nature of the returned populations.

MPS and OPI distributions in the 12 returned populations were proportionately higher than those found in the original population of tracers (Fig: 4.10). However, there were weak positive relationships (identified by linear regression) in the original population, between C-axis and both these parameters. A proportional increase in their values would be expected in returned populations containing larger than average C-axes. Some alternative explanation must be sought to explain the significantly lower roundness values found in the 12 returned populations, because there was no correlation effect in this case. Perhaps breakage occurred in the higher roundness categories without a compensating supply of increasingly rounded pebbles from lower roundness categories. If, and why, this should have been the case, and what effect it might have had on the distribution of other parameters was not clear. Certainly, breakage was observed, but no attempt was made to correlate its occurrence with changes in particle parameters.

4.4.2 Tracer/'Host' Test

During the course of the experiment, four checks were made of the relationship between individual tracers and their immediate neighbours on the beach face (termed the 'host population'). The test devised to assess this relationship involved remeasuring a 'randomly' selected tracer, and then measuring it and 30 of its immediate neighbours (Plate 9). The host population was considered to be that material lying on the beach surface in direct contact with, or no more than one pebble distant from the tracer. Generally, such material lay in the same plane as the tracer, although occasionally material in contact from below was also included in the sample.

A Chi-square test was used to determine whether the value of a particular tracer parameter lay close to those of its host population. The two quantities considered in this test were the number of host population pebbles with parameter values greater than or less than that of the tracer. If the proportions falling into each category were significantly unequal then the null hypothesis, H_0, that there was no significant difference between a tracer parameter value and those of its host population, was rejected at $p \leq 0.05$ or $p \leq 0.01$, with one degree of freedom. This non-parametric test removed any complications that could have arisen from the degree of sorting present in host populations. Parameters used in this test were the three principal particle axes, surface roundness, MPS and OPI.

The results are outlined in Table 4.5, which gives the number of test rejections at $p \leq 0.05$ for each parameter as a percentage of the sample number on each date. Clearly this test did not show the tracers becoming closer (in terms of their parameter values) to their host populations, which might have been expected to happen from the results of Richardson (1902) and others. In fact there was an indication that the opposite tendency prevailed. Only three percentage rejection scores fell below 50%; average scores varying between 60% and 69%. This further underlined the misfit character of the returned populations.

Since it was considered possible that smaller tracers (those lying within the normal part of the C-axis frequency curve in Figure 4.2) might have been more easily incorporated into the beach sediment, an attempt was made to see if those pebbles produced lower rejection percentages. No clear trend occurred, although the average thickness for non-rejected tracers was 6.7cm, while that for rejected tracers was 8.5cm. A similar attempt was made using MPS values, and this produced a more interesting result. Non-rejected tracers had sphericity values between 0.79 and 0.63, whereas rejected tracers generally had values higher or lower than this (Fig: 4.11). One explanation for this could be that since the injection point was relatively high on the beach face (Figure: 4.3), spherical tracers were subjected to shape sorting processes which eventually brought them down towards the base of the beach ridge. In reaching this position they may have found themselves more closely related to their increasingly spherical hosts. Unfortunately, no check was made of each tracer's relative beach position during the tracer/host tests.

4.4.3 **Discussion**

What mechanisms could be responsible for ensuring such unrepresentative returned populations, and the general dissimilarity between tracers and their host populations? A possible model can be developed from Moss (1962,1963). It was Moss's opinion that the initially deposited, dominant, exactingly selected particles, which formed the principal component of a water-lain deposit, played a vital role in determining what other particle types might also become incorporated within the accumulating sediment (section 3.4.2). The initially deposited material in his model was presumed to form as a result of particle interaction at the base of the traction carpet. Particles in this traction carpet could, if they were of the right size and shape, be incorporated within the developing deposit. If not they were 'rejected' and remained in motion as part of the traction carpet. Moss also refers to 'traction clog', in which the concentration of rolling and sliding particles exceeds a critical value, causing them to jam on the bed behind one or two particles which have prematurely halted.

Moss (1962,1963) based this work primarily upon the presumed depositional environment of a river bed. When applying the model to the behaviour of tracer particles on a natural beach surface, it must be noted that the indigenous beach material would constitute the initially deposited sediment, which was to a lesser or greater extent exactingly selected at the moment of depositon. As swash and backwash rhythmically disturbed the topmost layers of the beach surface, they would create a traction carpet. Processes which sorted the material would either maintain, reinforce, or reassemble its initial sedimentological compositon, depending upon the hydraulic forces operating and the characteristics of the beach particles. As this took place some tracers might have become selectively incorporated in the sediment, while others remained in motion in the traction carpet. Those which became incorporated would have then become characteristic of the sediment , whereas those 'rejected' and remaining in motion would only have come to rest on the beach surface if, and when, they settled out of the water between each translatory wave. A schematic picture of this selective process in operation is presented in Figure 4.12 (Caldwell, 1981).

If this model is correct it helps explain why tracers found on the beach surface were those dissimilar to the background beach material, because those which were similar would have been distributed throughout the whole layer of beach last subjected to disturbance by waves. It also provides an explanation for the misfit nature of the returned populations, since tracer material in close similarily to the bulk of the beach material would have become quickly incorporated within it at depth. This certainly illustrates the difficulties surrounding the use of tracer experiments to determine characteristic beach particle behaviour, particularly if returned populations only include those tracers located visually on the beach surface. Published results of tracer experiments do not usually include any description of the background population, or any assessment of how this material affected the performance of tracers in the traction carpet (Richardson, 1902; Kidson and Carr, 1961; Jolliffe, 1964; Carr, 1971; Gleason and Hardcastle, 1973; Gleason, et al., 1975). Some of these experiments used artificial materials (brickbats), or material gathered from beaches other than the one on which it was ultimately used. Under these circumstances it is possible to obtain consistently higher recovery rates than found in the experiment outlined here. Such alien material would have less chance of becoming incorporated within the indigenous beach sediment.

4.5 SUMMARY

A common method of identifying along-beach size sorting processes on pebble beaches has been through the use of tracers. Experiments of this kind have suggested that larger material can move further and at higher speeds, than smaller material. This work has indicated that for a given set of processses there is a certain size of material which will be selected for preferential transport.

To test previously published results, and to obtain some impression of the effectiveness of swash zone particle sorting mechanisms at work, a tracer study was carried out on Gileston beach. A new method was used to map the dispersion of marked material, and a detailed check was kept of the size, shape and roundness parameters of these particles. 12 distributions of tracers were surveyed, and a number of statistical tests performed on the data so produced. This showed that particle thickness (C-axis) was the most hydraulically susceptible parameter, and reasons for this have been given. Sorting mechanisms seem spasmodic on this beach, and it appears as if along-beach sorting processes could be a secondary response to down-beach sorting.

The relationship between dispersing tracers and background beach material was examined. Results of a test, which showed the unrepresentative nature of returned tracer populations, has been presented. So too have the results of some tracer/host tests which showed tracers to be generally dissimilar in character to the beach material with which they were in contact. A model has been proposed to explain these phenomena, and should it be correct it would question the results of tracer work which has been used to assess characteristic beach particle behaviour.

CHAPTER 5

PEBBLE BEACH MORPHOLOGY

"I would suggest to you the advantage, at present, of being very sparing in introducing theory in your papers (I formerly erred much in Geology in that way); let theory guide your observations, but till your reputation is well established, be sparing of publishing theory. It makes persons doubt your observations."

Charles Darwin, (in a letter to a young scientist), More Letters (1903), Murray, London.

5.1 PROCESS-RESPONSE MODELS

Modern sedimentological study of littoral environments has centred on the need to identify relevant facies models from the arrangement of nearshore sediments. Such an approach should take account of the stochastic nature of deposition and the depositional result of numerous random events. Analytical methods available for the identification of dominant facies sequences all depend upon a probabilistic basis, but there are only a few examples of such methods being applied to an extensive analysis of present day sedimentation. Whereas deterministic models purport to tell us what will inevitably happen, stochastic models make allowances for unpredictable events, and yet enable prediction of what is likely to happen. Stochastic analysis also enables the development of long-term equilibrium probabilities from short-term observations.

The limited range of potential facies attributes to be found on coarse clastic beaches has already been referred to in section 1.5. One of the vital attributes is the configuration or the morphology of the beach face. This parameter is particularly suited to stochastic analysis; its arrangement being the product of past and present processes and past configuration. Krumbein (1963) proposed a process-response model in which this complex relationship was identified. The response elements in the model include two main items as shown on the right-hand side of Figure 5.1. The first is the geometry of the beach deposit, which includes foreshore slope and width, height of berm, and width of backshore (for terminology see section 1.2). In a three-dimensional sense, the geometric element also includes the volume and shape of the beach deposit as a whole. The second item concerns the properties of beach material which are controlled by the kinds of material originally available at the beach site, or brought in by currents and tides.

Close relations occur among the process elements shown in Figure 5.1, in that the geometry of the beach site, as expressed by the configuration of the beach face, influences the pattern of energy distribution which it receives, both down-beach and along-beach. This is an example of interlock in that these two process elements are not wholly independent. According to Krumbein (1963, p8):

> "A beach deposit, formed by wave and current energy, may involve changes in the configuration of the bottom slope with time. These changes in turn modify the pattern of wave approach, so that a response element may exert feedback control on one or more process elements. These complexities are relatively common in process-response models...."

It should be noted that although the same attributes of the shore and beach materials are listed on the process and response sides of the model in Figure 5.1, those on the left represent initial properties, whereas those on the right are response properties. Figure 5.2 shows a few data-interlock and feedback relationships that occur in natural beach processes. This diagram indicates that the foreshore slope (beach face profile) is influenced by wave energy, shore currents, average grain size and the nearshore bottom slope. A response produced by the simultaneous effect of several factors (some of which may themselves be response elements), raises an important question in the evaluation of the relative effects played by each of the contributing factors.

Figure 5.3 is a rearrangement to indicate an alternative way of expressing the model (Krumbein, 1963) in terms of the beach profile and energy factors. In this variant, the energy factors (waves, tides and currents) are those acting on the foreshore.

Thus the beach profile is of great importance in influencing beach process-response relationships. It is an even more important characteristic of coarse clastic beaches where there is a general absence of primary sedimentary structures. It can be related to two major parameters of the depositional environment:

1. The hydraulic and energy characteristics prevailing across the swash zone.
2. The initial morphology and structure of the beach surface.

As Krumbein (1963) has stressed, these two parameters are inter-related and changes in one can induce changes in the other. Therefore a study of either, or both, is fundamental to the elucidation of morphology and process conditions upon which facies models can be based.

5.2 SONU AND VAN BEEK'S (1971) MODEL

In a classic study, Sonu and Van Beek (1971) proposed a beach-profile transition model derived from a study of 291 semidiurnal beach profiles measured on the Outer Banks of North Carolina (Dolan, 1966). They built their model in terms of beach width, sediment storage and surface configuration, and considered that it could be used to predict the development of successive beach profile changes, provided initial beach profile configuration and the stage in the development of a wave field was known. Their basic premise was that the sediment volume contained under a particular profile type was a stochastic function of past profiles and present processes (Sonu and Young, 1970; Sonu and James, 1973). Beach profile configuration is not amenable to analytical representation, but Sonu and Van Beek (1971) deliberately set out to characterise the beach profile as a system by using multiple parameters. This represented a considerable advance over previous studies which had confined themselves to single parameters such as beach-face slope (Bascom, 1951), local beach elevations (Shepard and Lafond, 1940; Inman and Rusnak, 1956; Harrison and Krumbein, 1964), or beach width (Dolan, 1966).

The new multiparameter approach involved classifying profile configurations according to two key aspects:

1.) The macro-form of the profile, or the shape of the smoothed trend of the profile.

2.) The absence or presence of accretional berms on the macro-form. The position of these berms was also noted.

According to Sonu and Van Beek (1971), there are three basic smoothed profile types; concave upwards, linear and convex upwards. Within fixed profile boundaries, the concave and convex types indicate configurations of minimum and maximum sediment storage respectively. Beach profile parameters were defined relative to the co-ordinates shown in Figure 5.4. The x-axis extended seawards perpendicular to the shoreline at mean sea level, whereas the y-axis extended vertically upward. The origin of the co-ordinates was located below a position marking the maximum landward limit of the swash front. In the context of the tidal range operating on the eastern seaboard of the U.S.A., beach elevation above the origin (denoted by h) remained essentially unchanged. S denoted the beach width and Q was the cross-sectional area bounded by the beach surface and the x and y axes, so that:

$$Q = \int_0^S y\,dx$$

This parameter, which is proportional to the volume of sediment contained in a subaerial profile seaward of the origin per unit length of shoreline, was called the 'sediment storage'.

Considering situations of minimum and maximum sediment storage respectively, these are achieved, according to Sonu and Van Beek (1971), when:

$$dy/dx = 0 \quad \text{at} \quad x = 0$$

and: $$dy/dx = 0 \quad \text{at} \quad x = S$$

By solving the differential equations for these storage limits, final equations were given as:

$$Q1 = 0.67hS \text{ (convex upward)}$$

$$Q2 = 0.33hS \text{ (concave upward)}$$

After empirical testing with Dolan's (1966) data, Sonu and Van Beek (1971) altered Q2 to:

$$Q2 = 0.45hS \text{ (concave upward)}$$

from which was derived the linear profile form (Q3):

$$Q3 = 0.5hS \text{ (linear)}$$

Sonu and Van Beek (1971) used these profile equations to obtain three distinct regression lines (Fig: 5.5). They asserted that when each of the 291 profiles was plotted in Q/S space, those classified according to a particular macro-form (concave, linear or convex) clustered around the regression line for this configuration-type. Sonu and Van

Beek (1971) did not specify any statistically significant differences between the regression equations (with respect to the regression β estimates) but attributed different sediment responses to their classification of profile differences.

As far as relative berm position was concerned (upper-beach, mid-beach or lower-beach), Sonu and Van Beck (1971) stressed its crucial importance in establishing profile sequence; its position is indicative of net sediment storage for the profile. By combining berm position with the three types of macro-profile, 12 possible configurations were established (Fig: 5.6). Data indicated that six configurations (denoted A, B, C, A', B', C' in Figure 5.6) occurred with greater frequency than others. Approximately 90% of all observed profiles could be classified into these six major configurations. According to Sonu and Van Beek (1971, p421):

> "....specific profile curvatures are produced by sediment distribution on the beach face. For instance, a relatively large deposit at the lower elevation of the beach results in a concave curvature [Fig: 5.6, type A]. As this situation is advanced, an increasing accumulation of deposit at the lower elevation should produce a concave profile with a lower berm. Similar reasoning will apply to a linear profile having an intermediate

berm and a convex profile having an upper berm, which represent, respectively, an advance state of localised sediment deposit at the intermediate and upper beach elevations."

In other words, the geometric properties of a beach profile are essentially governed by the distribution of an excessive local sedimentary deposit on the beach surface, known as the 'berm'. However, these investigators were unable to present a model which accurately distinguished between macro-profiles of a particular type, with and without berm development. In calculating equations in Q/S space for each of the three macro-profile types, they made an erroneous proposal that the development of a berm on any one of these configurations would extend the predictive range of the equation for that configuration. From a theoretical point of view, macro-profiles with berm development should occupy positions in Q/S space quite distinctive from that occupied by the same macro-profile types without berm development. Nevertheless, this methodology represented a significant tool for facies analysis and highlighted the need for a rigorous classification approach.

5.3 FIELDWORK

The first extensive field study to examine variations in beach morphology commenced in November 1977, when four cross-sections were selected on both Nash and Gileston beaches (Fig: 5.7 and 5.8). These were sited at approximately 300m intervals along each beach, so as to avoid the duplication of information inherent in Dolan's (1966) data used by Sonu and Van Beek (1971). For 12 months these eight cross-sections were surveyed at, or soon after, each consecutive spring high tide (section 3.3.2). Apart from the 192 beach profiles obtained during this period, further surveys (two at Gileston and four at Nash) were made in the following six months to make up a total of 216 profiles.

Then in February 1980 a smaller scale study (experiment 4 in section 3.3.2) was undertaken on Gileston beach to examine profile development during a spring-neap-spring tidal sequence. Daily surveys were made of six 'temporary' cross-sections located around cross-section 4 in Figure 5.8 and sited 20m apart, to enable three-dimensional reconstruction of the beach face. This same procedure was adopted in a similar experiment at Nash in March 1980 around cross-section 4 in Figure 5.7. These two studies produced a further 186 beach profiles.

Although these smaller-scale experiments gave rise to some duplication of information, all the profiles produced were used in the subsequent analysis because (1) there were, on many occasions, significant differences between them, particularly in terms of the position and magnitude of berm development, (2) daily changes in high-tide level meant that only a proportion of the total cross-section was usually affected by wave action and only this proportion (which often differed from profile to profile) was used, and (3) by making this selection, profile configurations which were poorly represented in the initial investigation could be obtained (further comment later).

The raw data was fed into the computer and profiles reduced to Ordnance Datum. This information was stored in memory, in 20 data files, each containing profile data pertaining to one specific cross-section (Appendix 5.1). Table 5.1 lists the cross-sections, beaches and types of experiment which gave rise to the 402 pebble beach profiles. Subsequent graphical and statistical analysis took place on the computer with the assistance of a Textronix (Graphics) V.D.U.

5.4 CLASSIFICATION OF THE PROFILES

Considerable difficulty arose when an initial attempt was made to classify profiles according to the procedure adopted by Sonu and Van Beek (Fig: 5.6). The fact that beach profiles had h_{max} values varying between 3-11m, and S_{max} values between 15-40m, meant that an objective visual assessment was difficult. Therefore each individual profile was subjected to standardisation based on trigonometric principles. Figure 5.9 shows how profile co-ordinates were recalculated so that the upper beach limit touched the h axis at a value of 5.290m, and the lower beach limit touched the S axis at a value of 30m, while the geometric characteristics of the configuration were preserved.

Let h_{max} and $\hat{h}_{max}$ represent the original and recalculated points at which the upper beach limit of a profile touched the h axis respectively, and S_{max} and $\hat{S}_{max}$ represent the original and recalculated points at which the lower beach limit touched the S axis respectively. Then if ϕ represents the angle between the S axis and a line drawn through the points $\hat{h}_{max}$ and $\hat{S}_{max}$, the recalculation of each co-ordinate on the profile (h_j, S_j) was undertaken thus:

$$\hat{h}_j = \frac{h_j\,(\hat{S}_{max} \tan \phi)}{h_{max}}$$

$$\hat{S}_j = \frac{S_j \;\hat{S}_{max}}{S_{max}}$$

where $\hat{S}_{max}$ and $\hat{h}_{max}$ were arbitrarily set at 30m and 5.29m respectively (thus the derivation of $\phi = 10°$). The selection of these values is relatively unimportant when using this methodology. They were chosen to produce profiles with proportions approximately equivalent to the unstandardised ones. This aided visual assessment during classification. These recalculated profiles were plotted according to the format shown in Figure 5.10. It was then easier to classify them objectively. Figure 5.11 shows upper and lower limits of the hypothetical 'sweep zone' (King and Barnes, 1964), calculated for all 402 standardised profiles. It indicated a maximum vertical variation of 2.5m and suggested that within this envelope was considerable scope for classification by profile configuration.

Table 5.2 shows how the profiles were distributed between 10 configuration types. It is evident that only concave and linear macro-forms were represented; a result in full agreement with Orford's (1978) work. Similarly, composite berm forms were also observed which either represented 'step and bar' profiles formed according to processes proposed by Orford (1977), or (more likely) were configurations on which were etched the 'memory' of previous berm positions together with a contemporary berm. That these profile types were relatively common (12% of total) was probably a function of the considerable tidal fluctuation which occurs in the Bristol Channel.

Of crucial significance in the classification process was the selection of that proportion of profile to be examined. In this context it should be noted that unlike Sonu and Van

Beek (1971) or Allen (1975), who were concerned with sand profiles extending below mean low water spring, only the pebble ridge on the upper foreshore was of interest to the current investigation. Furthermore, within this area certain limitations were put on the width of beach face which was examined.

For data which was gathered each spring tide, the relevant proportion was considered to be that lying between the ridge crest and its base. This presumed that the whole beach face along all eight cross-sections (Figs: 5.7 and 5.8) had come under the influence of waves between each spring tide cycle. Visual evidence suggested that such an assumption could not always be made (especially for the Gileston cross-sections). However, it was not possible to keep an exact record of high tide prior to surveying, and the assumption had to be made. This problem did not arise with data gathered on a daily basis since (with the exception of day 1) an exact record was kept of pre-survey high tide position. Therefore, only that proportion of beach which came under the influence of waves during the intervening 24 hour period was examined.

Because of the considerable porosity of pebbly material, it tends to become banked up at relatively steep angles (Zenkovich, 1967), where:

$$\beta = \sigma \quad \text{(maximum angle of repose)}$$

The angle β for any grade of material at a specific beach position, is that at which the force due to gravity (g) acting on the material exactly balances net swash forces predominating at that position. This of course ignores the complications of grain shape and imbrication.

Although pebble beaches experience internal water table changes of a similar nature to those observed on sand beaches (Emery and Foster, 1948; Grant, 1948; Duncan 1964; Strahler, 1964) there are important differences. Pore-space size determines the effectiveness of surface tension in the water retention properties of particulate material. The large pore-spacing apparent in pebble-sized material means that the influence of surface tension is almost negligible and there is therefore much less water-table lag during a tidal sequence, than found on sand beaches. Furthermore, because of the relatively greater increase in beach height (h) per unit length of beach width (S) on pebble beaches, it is unlikely that the area close to the beach ridge crest becomes fully saturated during a tidal cycle, because sub-surface drainage is too effective. This means that net swash forces are greatest at, or immediately behind, the swash tip, while they fall rapidly in value seawards of this position. For this reason, beaches made of coarse clastic material are more likely be concave upward in configuration, with the steepest beach face angle (β) usually observed just below the beach crest (Caldwell, 1982).

Although those profiles which included the beach crest were more likely to be concave in configuration, selected sections of the lower beach portion of other profiles were almost equally likely to fall into either the concave or linear categories. In fact 81% of the 216 profiles gathered at spring tide intervals fell into concave categories, while only 51% of the selected proportions of the 186 profiles gathered on a daily basis fell into these categories. This stressed the care with which any interpretation of results had to be made.

Figure 5.12 substantiates the accuracy with which profile classification was made. All standardised profiles in each of the 10 configuration type categories were used to compute an average profile. Each of these average profiles is plotted in Figure 5.12 alongside an idealised model for that category. Standard deviations each side of these average profiles are also shown at 1m intervals. For all 10 categories, agreement with the idealised model is excellent and shows the effectiveness of using a standardised visual format for classification.

5.5 STATISTICAL ANALYSIS

Profile classification groupings (Table 5.2) were statistically tested for between-group heterogeneity. Orford (1978), in the only previous attempt to classify pebble beach profile configuration, failed to produce significant statistical evidence of the heterogeneity of profile populations in specific categories. He put this down to the fact that "....the ratio of berm material volume to beach material is only small to negligible" on pebble beaches (Orford, 1978, p309); a matter which the present author disputes. Orford (1978) computed regression lines in Q/S space (along the lines proposed by Sonu and Van Beek, 1971). Because of tidal problems which caused fluctuations in his h and S values, Orford (1978) had to modify the calculation of Q as a means of standardising between profiles. Such a modification is not necessary with data which has already been graphically standardised. Orford (1978) then attempted to isolate significant differences between the β estimates of his computed regression lines. Unfortunately, he found none, and had to subjectively reclassify his profiles as step, bar and composite (Fig: 5.13), as the basis for his facies model (section 1.8).

Initial h_{max} and S_{max} values will determine where resulting Q values will lie in Q/S space, and this can make direct comparison between different beach profile data difficult. A methodology was needed which made profiles independant of their h_{max} and S_{max} values. This was accomplished by making use of the concepts of hypsographic curves and hypsometric integrals, used frequently in fluvial geomorphology (Holmes, 1965). Each profile was considered to represent a hypsographic curve from which a hypsometric integral could be derived. The integral was represented by the area under the curve expressed as a proportion of the area of the square of which h and S axes formed two sides. The integral was expressed as a value between 0 and 1. This value could be derived from each profile at any time, although it was more easily obtained after graphical standardisation when every profile had the same h_{max} and S_{max} value. The integral represented a one-dimensional description of the profile configuration.

Figure 5.14 shows how the integrals for each profile were plotted to identify possible differences between the populations of profiles in each category. The numbers 1 to 10 refer to configuration types A to J shown in Figure 5.12, while 11 and 12 represent all concave and linear-type profiles containing a berm in any position respectively. In order to establish statistically significant differences between these 12 populations of integrals, an F-test was first used to determine equality of variances, and therefore whether a parametric or non-parametric test would be appropriate. It indicated that the assumption of equality of variances could not be guarenteed, although F values often lay close to the borderline of acceptance or rejection. This is explained by reference to Figure 5.15 which shows how frequency distributions of the 12 populations often approximated the normal.

Nevertheless, a non-parametric test (the Mann-Whitney U Test) was chosen for statistical analysis and the results are shown in Figure 5.16. There is a pleasing symmetry about the matrix which provided evidence of the statistical difference between:

1. Concave profiles without a berm and concave profiles with berm(s).
2. Linear profiles without a berm and linear profiles with berm(s).
3. Concave profiles with and without berm(s) and linear profiles with and without berm(s).

Key differences are indicated in Figure 5.16, and were all established at $p \leqslant 0.001$ which underlined the effectivness of the classification. This was therefore strong and convincing evidence that profile morphology could be used to distinguish between facies types provided that evidence was available to explain the genesis of different morphologies in depositional terms.

5.6 **GENETIC IMPLICATIONS OF DIFFERENT PROFILE CONFIGURATIONS**

Sonu and Van Beek (1971) used their classification system (Fig: 5.6) to analyse systematic beach profile changes observed over a period of six months. They identified a cyclic transition model which restricted erosion and deposition pathways through certain profile configurations, and they managed to correlate specific steps within this stochastic model with particular wave directions, and thus (in the context of the North Carolina coastline) with the growth and erosion phases of storm wave fields.

It is difficult to identify a clear relationship between concave or linear macro-profiles and specific wave processes. The change between concave and linear conditions simply indicates the deposition of a veneer of sediment over a wide area. A change in the opposite direction would imply erosion of the same general character. But the presence or absence of a berm and its relative beach face position, could be of crucial significance in identifying a range of process conditions, each providing distinctive depositional arrangements. Several authors have already linked berm development with specific nearshore wave conditions (reviewed by Johnson, 1919, p404-458; King, 1972, p314-364; Davies, 1973, p130-133; Komar, 1976, p289-325).

Komar (1976) utilised the terms 'swell profile' for summer fill, and 'storm profile' for winter cut. Kemp (1961) observed berm-like features developed at the upper and lower beach limits in swell and storm profiles. Lewis (1931) noted that beach profiles with an upper berm (step) usually developed under the influence of swell waves (waves with a low amplitude relative to wave period). These waves were 'constructional' and transported sediment onshore, building up the beach face. According to Lewis (1931), storm waves (waves with a high amplitude relative to wave period) produced the opposite effect, moving sediment offshore and depositing it under or seawards of the breaker line. These waves were 'destructional' and produced one or more lower beach berms or bars.

On sand beaches, the distinction between sub-aerial swash-formed features, which produce step profiles, and submarine break-point bars (bar profiles) is usually clear. This clarity can sometimes be obscurred on a pebble beach if its base does not extend below low water level (e.g. at Gileston and Nash). Under storm conditions a pebble beach break-point bar forms exactly as it would on a sand beach. However, as it migrates with tidal translation, it eventually becomes stranded during the ebb tide, at the ridge base. As tidal level continues to fall, this stranded bar often becomes more pronounced as a result of constructional processes occurring at the swash tip (Orford 1978). Such action creates a major break of slope at the foot of the beach ridge which is morphologically analogous to a swash-formed berm.

Considerable laboratory and fieldwork has gone into assessing genetic implications of the step/bar profile model. Initial discrimination was made on the basis of a critical offshore wave steepness criterion:

$$W_s = H_o / L_o$$

where H_o = deep water wave height, and L_o = deep water wave length. The large range of published critical W_s (Johnson, 1949; Rector, 1954; Watts, 1954; King, 1972) suggests that, despite the obvious importance of W_s , modelling a complex, multi-dimensional situation on only a single parameter is imprecise. Responding to this problem, Kemp (1960) introduced the concept of swash 'phase-difference', calculated by :

$$pd = t / T$$

in which T = breaking wave period, and t = swash period (or the average time taken for waves to pass from break-point to swash limit). When $pd<0.7$ a 'surge phase' prevails in which there is very little impedance of incoming waves by outgoing backwash, and net sediment movement is onshore. When $pd>1.2$, impedance of swash by backwash is such that a circulatory flow-system is established which results in net sediment movement offshore.

Iwagaki and Noda (1962), Nayak (1970) and Sunamura and Horikawa (1974) all tried to elaborate on the W_s approach with varying degrees of success. Sunamura (1975) developed this multi-dimensional approach by producing ever more complex formulae which included such aspects as wave height, phase difference, beach slope and sediment diameter. He derived a dimensionless value (C) which acts as a discriminant between step and bar profiles for any given wave steepness or beach situation. C can be found from :

$$C = (\tan\beta)^a (d/L_o)^b / W_s$$

where β = initial beach slope angle, d = mean sediment diameter and L_o = offshore wave length. When C<4 a step profile is produced, and when C>4 the result is a bar profile. Subsequent field testing has suggested that C=9 is a more realistic transitory value - the difference being attributed to scale factors (Sunamura, 1975).

Sunamura and Horikawa's (1974) profile classification was as follows :

<u>TYPE I</u> C>9 and the shoreline advances onshore with subsequent erosion and the development of a break-point bar.

<u>TYPE II</u> C<9 and the shoreline retreats offshore with accretion and development of a swash berm or step.

<u>TYPE III</u> C=9 and initial shoreline retreat is followed by an advance in which both a swash berm and offshore bar is developed.

Orford (1977) was particularly interested in the Type III classification since it matched his 'composite profile' type (section 1.8.8). Such profiles stressed the importance of negative feedback (Fig: 5.2), which operates as the initial profile is altered. This alteration can subsequently induce a change in breaker structure and therefore swash zone depositional characteristics. Despite this, some 'composite profiles' may simply be profiles on which there are relict berms produced by constructional processes associated with differing tidal levels.

It has now become generally accepted that shallow water situations, which encompass the breaker and swash zones, cannot be accurately modelled by use of deep water wave indices. This explains to some extent the difficulties experienced in the application of W_s values. Kemp's (1961), 'phase-difference' was an attempt at overcoming this problem. Galvin (1968, 1972), Sawaragi and Iwata (1974), Huntley and Bowen (1975), Kemp (1975) and Miller (1976) have all developed an approach which inculcates the importance of wave breaker type on swash zone flow conditions, and hence on net sediment movement. Wave breaker type is controlled by shoaling slope and deep water W_s. Galvin (1972) proposed a breaker steepness index :

$$B_s = (H_b / gT^2)^{\frac{1}{2}}$$

where H_b = breaking wave height, g = acceleration due to gravity and T = wave period. B_s has been shown by Galvin (Fig: 5.17), Harrison (1970) and Gaughan and Komar (1975) to be an effective discriminator between different breaker types and therefore different sedimentary processes.

Different breaker types have also been associated with particular profile configurations. However, this evidence suggests some inconsistency (Hayami, 1958; Orford, 1977, 1978), and it appears that in certain circumstances both plunging and spilling breakers can be associated with either step or bar profiles. On theoretical grounds it appears that changes in beach slope rather than W_s, have a greater influence on breaker type (Gaughan and Komar, 1975). If W_s is held constant then breaker type changes from a spilling to a plunging to a collapsing to a surging mode as beach slope increases (Galvin, 1972). It is quite possible, therefore, that in an area of large tidal changes, waves breaking on the steep convex face of a pebble beach will change in breaker type as the tide flows and ebbs. This effect is accentuated by the addition of a storm-surge component (Orford, 1977).

It is obviously tempting to establish an explicit relationship between profile type and breaker type because such an approach would help to provide some genetic explanation. After all, the objective of using differing profile configuration as a discriminant between various facies types is to associate specific facies with particular hydraulic conditions operating in the nearshore zone. Despite the contractictory evidence provided by published sources, Orford (1977) attempted to establish a logical framework from which his facies model could be derived. On the basis of a relatively small number of observations (N=28) Orford (1977) estimated upper and lower B_S boundaries (shaded zones in Fig: 5.18). These suggested the possibility of associating step and bar profiles with ranges of B_S, for a given shoaling slope angle.

It is interesting, however, that these estimated B_S boundaries do not coincide with Galvin's (1972) breaker type boundaries (Fig: 5.17; dashed lines in Fig: 5.18), so that on this basis both plunging and spilling breakers could be related to the development of step profiles. Nevertheless, Orford's (1977) proposal represented a definite advance, however tentative the evidence, since it sought an explanation for profile morphology and facies type in terms of nearshore hydraulic processes.

5.7 OBSERVED PEBBLE BEACH MORPHOLOGICAL CHANGES

Having evolved a definitive methodology for the classification of profile configuration, tested its statistical significance and provided some genetic evidence to support its role in facies modelling, this procedure was used to provide information about morphological changes observed during the experiments on Gileston and Nash beaches. In order to identify possible patterns in the morphological behaviour of the total of 20 cross-sections monitored during different periods of fieldwork, data were presented in three forms:

1. Figures 5.19A-D, 5.20A-D, 5.21A-F and 5.22A-F show profiles obtained for each of the 20 cross-sections plotted in a three-dimensional format. As such, each diagram represents a time-lapse record of the morphological changes observed along each cross-section. The time interval between each profile in Figures 5.19A-D and 5.20A-D is one spring-neap-spring tidal cycle, whereas in Figures 5.21A-F and 5.22A-F it is approximately 24 hours. Figures 5.23A-Q and 5.24A-N represent three-dimensional reconstructions of the actual beach face surveyed on Gileston and Nash beaches, respectively (experiment 4, section 3.3.2). Each block diagram shows the morphology of all six 'temporary' cross-sections as recorded on one daily survey.

2. Figures 5.25A-J, 5.26A-J, 5.27A-J and 5.28A-J show matrices drawn to identify patterns in the systematic occurrence of the 10 types of profile configuration on each cross-section during each experiment.

3. Figures 5.29A-T show graphs displaying the systematic changes in profile configuration observed on each cross-section over time. Symbols have been used to represent changes in berm position, whenever they were present.

Each of these three different formats enabled various patterns in the profile data to be observed. An explanation of the information they contained is given for each of the four experiments.

5.7.1 <u>Gileston Beach from 10.11.77 to 20.02.79</u>

Figures 5.19A-D, 5.25A-J and 5.29A-D showed that during the early monitoring period (10.11.79 to 09.02.78) beach configuration along cross-sections 2,3 and 4 (Fig: 5.8) was essentially concave with no berm development (Fig: 5.25A). In contrast, cross-section 1 maintained an upper berm (Fig: 5.25B). During a transition phase (09.09.78 to 10.03.78) all cross-sections showed the formation of a concave macro-profile with a mid-beach berm (Fig: 5.25C). This configuration was generally maintained until at least 19.10.78 on cross-sections 1,2 and 4. Cross-section 3 showed a cyclic variation between concave, mid-berm and concave, no berm (Fig: 5.29C). Other minor variations were the cyclic transition between concave , mid berm and concave, composite berm on cross-section 1 (Fig: 5.29A), and the cyclic transition between concave and linear macro-profiles on cross-section 2 (Fig: 5.29B).

The overall pattern, however, was seen in the formation of a mid-beach berm on all cross-sections at approximately 6.5m O.D. (Fig: 5.19A-D). The last two surveys on 13.12.78 and 20.02.79 showed a change for all cross-sections, and then a return to concave, mid-berm for cross-sections 1,2 and 4 (Fig: 5.25C) and a concave, composite berm morphology for cross-section 3.

With only one exception (cross-section 4 on 13.12.78 - Fig: 5.25I), all 103 of the recorded profiles for Gileston beach showed either no berm development (N=30), or the formation of mid and/or upper beach berms (step profiles). The vast majority had concave macro-profiles. This was partially due to the decision to select the complete beach face profile, from ridge crest to base, for analysis (section 5.4). Where linear configurations were developed (N=10) they represented generalised accumulations over the lower beach area. Thus beach morphology throughout the study period showed more or less stable phases which corresponded well with 'winter' and 'summer' seasons. This relatively low level of morphological change reflected the results of the tracer study on Gileston, during which only five significant changes in the distribution of dispersing tracers were observed over a 14 month period (section 4.3.4).

5.7.2 **Nash Beach from 14.11.77 to 16.08.79**

Reference to Figures 5.20A-D, 5.26A-J and 5.29E-H showed that the four cross-sections on this beach (Fig: 5.7) gave rise to a great variety of berm positions. A concave macro-profile type dominated, with only 24 out of 112 profiles falling in linear categories. Unlike the results for Gileston beach, those for Nash showed little pattern in terms of the occurrence of common configuration types on different cross-sections, at any one time. Apart from cross-section 2 between 09.03.78 and 20.09.78 (Fig: 5.20B and 5.26G) results showed an overwhelming tendency for beach morphology to have changed (both in terms of the existence and position of beach berms) between each survey.

It was therefore impossible to characterise beach morphological developments at Nash along the same lines as were suggested for Gileston. There were only eight occurrences of a lower berm (bar profile), although a number of the 17 composite berm profiles included a berm at this position. That the beach is unstable in terms of its morphology is probably due to several factors :

1. Its position in a high-energy environment (Fig: 1.3).
2. The fact that it is restrained by acliff-line and cannot migrate inland (as in the case of Gileston beach) to a position at which increased shoaling

distance would lower wave energy levels.

3. The fact that it is both backed and underlain by an impervious surface which enables water-table levels to rise and thus increase the effectiveness of backwash under certain conditions. This is again in contrast to Gileston beach which allows sea water to drain landwards during spring high-tide phases.

Nash beach was therefore more active than Gileston beach during the study period, and showed a great variety of morphological response both between cross-sections at any one time, and along any one cross-section over time. It could be expected that this level of response would be reflected in the pattern of beach particle zonations observed.

5.7.3 Gileston Beach from 02.02.80 to 18.02.80

Reference to Figures 5.21A-F, 5.23A-Q, 5.27A-J and 5.29I-N showed that while overall beach face morphology remained essentially stable from beach crest to toe, a variety of minor changes were recorded along those proportions of the six cross-sections subjected to the influence of waves during each high-tide. Table 5.3 provides information on the littoral conditions observed during the experiment. Squally, storm conditions were recorded over the first three or four days with gale force 9 winds blowing on Sunday (night)

03.02.80. However, wind direction was not stable, switching from SW to E and then back to SW. As a result no wave field of homogeneous origin developed and wave energy levels (H_b) were relatively low. Where berm development was apparent, it was located on the upper beach, and macro-form shifted between linear and concave on a number of cross-sections.

During days five and six (Table 5.3) cold, rain-bearing easterly and northeasterly winds dampened the south-westerly swell, and wave period lengthened. Between days seven and 11 the wind remained southwesterly as tide level fell to neap. A whole range of berm positions were recorded and linear macro-forms were observed because only the lower half of the beach was being affected by the southwesterly waves. A more regular wave pattern developed during this period, giving rise to a slightly increased breaker height (H_b) and a spilling breaker form.

As tide level rose to spring between days 12 to 17, winds first veered easterly before conditions became calm. Wave period lengthened before wave disturbance also died down by day 16. Breaker height fell steadily and breakers were of the plunging mode. Where berms were developed they tended to be of the upper-beach type, and macro-forms returned to concave (if they had previously been linear) as the whole beach face width was affected by waves again.

Figures 5.27A-J showed a remarkable lack of pattern, so far as profile configuration was concerned, between the six cross-sections at any one time. The only exception to this was observed on the last day of the experiment when, despite local easterly winds, a fresh southwesterly wave train became active (T =7.0secs, H_b=2.5'). This had the effect of removing evidence of berm development. This general lack of pattern between the closely spaced cross-sections was probably due to the relatively low wave-energy levels prevailing, and the lack of any coherent wind/wave pattern.

5.7.4 **Nash Beach from 18.03.80 to 01.04.80**

Reference to Figures 5.22 A-F, 5.24 A-N, 5.28 A-J and 5.29 O-T provided evidence of several distinct phases of profile development. Littoral conditions (Table 5.4) mirrored these phases in many respects. The first phase, from day one to day five or six, brought cold northeasterly winds. Waves were short period, locally derived and of low breaker height. (It is not uncommon in localities where topographic effects are important, to observe locally derived waves and winds coming from different directions). During this period the cross-sections showed both concave and linear macro-forms. Where a berm was developed it was positioned on the lower beach. Such configurations as were recorded were largely inherited from pre-spring tide conditions, and the low wave energy levels of this first phase did little to alter them.

It was unfortunately impossible, for logistical reasons, to survey the beach on day six, but by day seven significant morphological changes had taken place along all cross-sections (Fig: 5.24F). A berm had formed at mid-beach position. (Because of the tide level, which determined the upper limit of beach profile chosen for examination, this berm was recorded as an upper beach berm, or, where there was evidence of some morphological change landwards of this berm, as a mid-beach berm). However, the berm was essentially developed at the high tide level. Because of the lack of information about littoral conditions on day six, it was difficult to pin-point any specific reason for the development of this step-profile morphology (Table 5.4), however, breaking wave height (H_b) had significantly increased by day seven. These waves were relatively 'young' (T_b = 5.0 to 6.0 sec), broke either in the plunging or spilling mode, and emanated from the southwest.

The second phase, which lasted until day 11, saw breaking wave height and wave period increase, with a return to plunging wave conditions. As tidal levels rose to spring, these waves pushed the berm up the beach face (Figs: 5.24 G-J), whereupon, on day 12, a dramatic change took place. This third phase, which lasted 24 hours, saw the beach being combed down to record lower berms on all six cross-sections.

Macro-profiles were concave, in all but one instance, and because of the non-removal of inherited upper beach berms on cross-sections 4, 5 and 6, these profiles were recorded as concave with composite berms (Fig: 5.28E).

It is worth noting that the proximity of Nash Point (Fig: 5.7) had caused dominant waves during early 1980 to be reflected in such a way as to lower beach ridge crest height immediately to the northeast. The study area during this experiment included the limit of this lower crestal section, so that cross-sections 1 to 3 had lower ridge crests than cross-sections 4 to 6. These latter cross-sections showed the development of an upper beach berm which was not affected during the experiment and which was therefore not included in the majority of profiles subsequently analysed. Bar profiles observed on day 12 were the result of a south westerly wave field producing large breakers (H_b = 4.5') with a long period (T_b = 11 sec). These were swell waves emanating from the mid-Atlantic, enhanced by a fresh southwesterly breeze active locally. This wave pattern soon degenerated so that by day 13 wave heights fell to 1.8'. Thereafter, until the end of the experiment, a new wave field (T_b = 9 sec, H_b = 1.0' to 2.0') became effective. This covered the fourth and final phase during which the lower beach berm was removed, and there was some development of an upper beach berm. At this time the beach was making a slow recovery from the 'destructive' bar-profile-forming third phase, to a 'constructive' step-profile-forming fourth phase.

5.7.5 **Summary of Morphological Changes**

Despite the clarity afforded by the classification procedure, results were often complex and lacking in any obvious pattern. At certain times specific morphologies could be observed concurrently at a variety of beach locations. Such morphologies could be related to contemporary littoral conditions. It was remarkable, however, that at other times, even cross-sections located no more than 20m apart showed considerble morphological variation. This underlines the difficulty of applying generalised facies models for a given set of littoral conditions. It was apparent that localised variations in swash zone hydraulics and/or initial slope morphology and sediment characteristics, could give rise to a range of ultimate configurations.

This would appear very much in agreement with recent work by Carr et al. (1980). These investigators have argued that, considering the entire beach system, "....there is no uniform trend of erosion or accretion, nor a progressive variation in beach elevation or volume alongshore, from one survey to the next." (Carr et al., 1980, p267). It is interesting to note that in an analysis of topographic surveys carried out in Start Bay (Gleason et al., 1975), along the eastern shore of Swansea Bay (Blackley and Carr, 1977, 1980), and between Aldeburgh and Southwold (Blackley, 1979), there was little evidence of consistent trends in profile configuration along each beach. Even when some consistency in trend occurred, it did not represent a high proportion of the annual variability in profile volume change. Carr et al. (1980, p279) therefore concluded, "....it is the difference in the frequency of beach height fluctuations over a period which is important rather than the 'classical' concept of drawdown associated with 'winter', and accumulation associated with the 'summer' season."

Not only do the results presented here substantiate the common lack of trend which can occur over a section of beach face, but an examination of Gileston and Nash sweep zones for 'winter' and 'summer' periods using the spring tide interval data (results not shown here) clearly demonstrated the accuracy of the above quoted conclusion. In addition, it has been mentioned that longshore redistribution of material often accounts for net depositional or erosional configurations being realised at any point. There is certainly no direct connection between upper beach cut and lower beach fill, or the reverse process. This too appears to agree with the findings of Carr et al. (1980). Although it is frustrating to observe situations in which there is some consistency of trend, and then others which show none, some solace can be found in the view of Lueder (1954) who wrote: "Beaches are exceptionally complex features whose major characteristic is variability."

5.8 SUMMARY

Beach facies modelling requires an approach which takes account of the stochastic nature of beach change. One important facies attribute which can be used in resolving a facies model for coarse clastic beaches, is that of profile configuration. This parameter displays stochastic control, and provides evidence which forms a non-stationary Markovian process because configuration is partly a function of the preceeding profile. This has enabled both theoretical and numerical modelling to be undertaken.

No attempt has been made here to model profile development along such lines. The reason for this is that the number of profile transitions recorded for each cross-section was too low (max = 28 profiles). Neither were these in strict semi-diurnal sequence, and they could not therefore be used in Markov analysis. Nevertheless, the methodology outlined here does represent the best means of preparing profile data for stochastic interpretation.

Using Sonu and Van Beek's (1971) approach (developed for a micro-tidal sand beach environment) a successful classification system has been proposed for pebble beach morphological investigations. This system distinguishes between different profile configurations at a resolution that has proved statistically significant at $p \leqslant= 0.001$. A number of refinements have been made to the original model of Sonu and Van Beek (1971), which should enable more widespread use of its potential. These are:

1) Angular standardisation of profiles (Fig: 5.9) which overcomes problems caused by variation in h and S values between different profiles. This enables a more accurate visual classification to be made.
2) Adaption of the concepts of hypsographic curves and integrals to beach profile study. The integral (Fig: 5.4, section 5.5) represents a one-dimensional description of profile configuration, and always lies between 0 and 1.
3) Derivation of a 10 category classification system (Fig: 5.12) of particular relevance to coarse clastic beaches.
4) Statistical proof that not only the profile macro-form (concave, linear, convex), but also the existence or non-existence of a berm can be distinguished by adopting the integral approach (Fig: 5.16, Table 5.2).

A body of literature has been reviewed which (despite some inconsistency) suggests that berm development and position can be related to swash zone depositional conditions. Actual quantitative description of these processes has proved difficult because of the complex hydraulic forces operating, but profile configuration represents a finger print of previous swash/backwash action.

In four investigations, profile configuration has been effectively used to describe process and form changes over a variety of timescales and spatial resolutions. It has highlighted the spatial and temporal variety in form that can be observed under apparently similar littoral conditions. This suggests some insufficiency in a two-dimensional approach that has no regard for regular and irregular along-beach morphological changes (e.g. cusps). Some morphological patterns were discernable which could form the basis for amended or refined models of pebble beach sedimentation.

Throughout the investigation, differences between sand and pebble beaches have been noted. In general terms it is not appropriate to apply sand beach terminology and investigative methodology directly to pebble beaches. Key differences can be summarised as follows:

1) The relatively larger particle size on pebble beaches which reduces the role of surface tension and inter-

pore water retention. This in turn reduces water-table lag time and enhances the constructive power of swash.

2) The relatively steeper beach face angles on pebble beaches arising from the above characteristics.

3) The predominance of concave macro-forms on pebble beaches (crest to base), with linear forms confined to the lower beach portion.

4) The relatively smaller width of fringing pebble beaches which do not extend below low water level. This can affect the development of certain types of morphology.

5) Because fringing pebble beaches have a restricted width, changes in morphology cannot necessarily be related to absolute variations in sediment storage, as is seen in offshore/onshore sediment transport on sand beaches. Instead, longshore redistribution of accumulations of material is a more realistic explanation for pebble beaches.

Given these differences, adapted methodologies (such as that outlined in this chapter), need to be produced to enable detailed study of pebble beach behaviour.

CHAPTER 6

PEBBLE BEACH SEDIMENTOLOGY

> "Nevertheless, we must believe that the strata undermined by the waters of this ancient strait, were broken up into huge fragments, and these lying scattered on the beach, were reduced first to smaller blocks, then to pebbles, and lastly to the most impalable mud, which the tides drifted far into the eastern or western ocean"

Charles Darwin, 26th April 1834, (on the formation of the Strait of Magellan), Journal of the Voyage of the Beagle.

6.1 INTRODUCTION

In section 1.7 and 1.8 of this thesis two models of pebble beach sedimentation were presented, (Bluck, 1967; Orford, 1978), and the major differences between them identified. Sediment data was gathered from the two study beaches with the object of throwing more light on this subject. The main questions to which this work was addressed were as follows:

1. Could the generalized zonational structure observed by both Bluck and Orford be identified on these beaches?

2. If there were differences in the expression of this structure on each beach, what were they and why did they occur?
3. If the zonational structure was present, did its expression vary spatially and/or overtime?
4. If spatial or temporal variations occurred, could these be related to morphological changes, and therefore to probable genetic processes?

6.2 PRESENTATION OF RESULTS

6.2.1 Analytical Work

Data from 37,080 beach pebbles, each represented by their A,B,C-axes and surfaces roundness, were used to elucidate sedimentological aspects of the two beaches. In addition, Maximum Projection Sphericity (MPS) and Oblate-prolate Index (OPI) was computed for each pebble. To facilitate the use of Zingg's (1935) shape classification (Fig:3.1) the ratios B/A and C/B were also computed. For each sample of 30 pebbles, the sample mean and its standard deviation were calculated. Other analytical methods also required specific transformations of the original data. The manipulation of millions of bits of information presented a major task.

It was difficult to generalize this large quantity of information. In choosing a suitable statistical methodology (section 3.4.4), intense reduction of data using sophisticated statistical methods was avoided. However, this also meant that the amount of reduced data from which interpretation was made, remained large. To avoid confusion, therefore, an ordered approach to interpretation was maintained. This moved from an examination of the the macro to the micro-sedimentological characteristics of material.

Stage 1 Examined all sediment collected from both beaches. Two populations of data were used; one gathered by selective sampling (section 3.3.1) and the other by grid sampling (section 3.3.2). Since the former approach was more commonly used, this is referred to as the 'standard' sampling method. In fact 31,080 pebbles were sampled using the standard method, whereas only 6000 pebbles were sampled using the grid method.

Stage 2 Examined differences between sediments on the two beaches. This involved both standard and grid data.

Stage 3 Examined along-beach sediment variaton on each beach. Only standard data was used because (1) the sample size was largest, (2) it was accompanied by morphological information (Chapter 5), and (3) the location of sample points were selected with this analysis in mind. A non-parametric statistical test (the Kolmorogov-Smirnov Two Sample Test) was used to test the significance of any spatial variation.

Stage 4 Examined down-beach sediment variation. A similar approach to stage 3 was used to test differences in sediment composition between the A,B,C1,C2,D or E sediments (Fig:3.6).

Stage 5 Examined relationships between sediments (sub-facies) and profile morphology. This was designed to elucidate factors governing the genesis of pebble beach sedimentology.

6.2.2 Standard and Grid Sampling Methods

Figures 6.1 and 6.2 show how a grid of 50 sampling points was set up, using cross-section 4 as a base-line, on Nash and Gileston beaches, respectively. 30 pebbles were sampled at each point, making a total sample of 1,500 pebbles in all. Two samples were made at Nash, on 8.10.79 and 2.1.80, and two at Gileston, on 24.9.79 and 18.12.79. Thus 6,000 pebbles were sampled by this method.

Figures 6.3 to 6.10 show the consecutive profiles obtained from all eight 'permanent' cross-sections on Nash and

Gileston beaches gathered during Experiment 1 (section 3.3.2.). Also shown are the selective sampling positions (note that the E sampling position is not shown as it always lay on the foreshore platform, and the A sampling position is not shown for those cross-sections on which it lay behind the ridge crest). Only those samples measured each spring tide between 10.11.77 and 20.10.78 were used in the sediment analysis, making a maximum of 24 samples for each point. Figures 6.11 to 6.18 summarize the location of these sampling points for each cross-section. It can be seen from these that sample points A,B and E were restricted to very narrow zones on the storm or back-beach, the upper beach face and foreshore platform respectively. Sample point D was restricted to the beach toe area, although its exact location varied within 5m or so. Sample points C1 and C2, being associated with mid-beach berms and/or distinct changes in sediment composition on the beach face, were those which varied in location by the greatest amount; up to 10m. On Gileston beach, these two sampling points were located in a slightly different position compared with those at Nash. This was largely a reflection of the location of mid-beach berms on either beach during the monitoring period.

6.2.3 Graphical Presentation of Results

The data were used to construct five different types of graph giving information about size/shape relationships. Bluck (1967) used this approach to establish his model of pebble beach sedimentation. According to Bluck (1967, p149), its great advantage over moment measure (size) analysis results from its ability to, "....dissect the frequency curve in such a way as to permit a more direct analysis of where, to what extent, and how gravel movement is, or has taken place in the area represented by the sample".

The five different types of graph were constructed as follows. One of the three potential size parameters (A,B or C-axis) was chosen. Initially it was the C-axis, although this choice led to the discovery of crucial size/shape relationships which resulted in recalculation of certain results using the A and B-axes. A computer program was written which examined the nature of particles falling consecutively into 1cm discrete units between 0.0 and 49.9 cm when using the B or C-axis to represent size, and between 0.0 and 99.9 cm when using the A-axis. The following information was obtained for pebbles falling into each discrete unit: (1) the percentage of blades, discs, rods and spheres, (2) mean MPS, (3) mean OPI, and (4) mean surface roundness. A record was also compiled of the mean values of the two pebbles axis parameters not chosen to interpret size. Examples of the data files thus computed are provided in Appendix 6.1.

These values were then plotted as follows:

1. The percentage of blades, discs, rods and spheres recorded for each discrete unit were plotted in relation to the size-frequency distribution curve of the sample. Such graphs are shown in Figures 6.19 AA-QB, and they represent one of the two principal analytical methods used by Bluck (1967). The four curves on each diagram divide its area into four proportions. That beneath the first line reflects the percentage occurrence of blade-like particles in the sample. That between first and second lines reflects the percentage occurrence of disc-like particles. That between the second and third lines reflects the percentage occurrence of rod-like particles. And finally, that between the third and fourth lines reflects the percentage occurrence of sphere-like particles.

This is a different sequence to that adopted by Bluck (1967), whose order was spheres, discs, rods and blades. This sequence unfortunately juxtaposes the two 'end-shapes' (spheres and discs) and cuts them off from their respective 'intermediate shapes' (rods and blades). A more reasonable sequence, which would reflect progressive shape change, would be: discs, blades, rods and spheres. This is not simply a geometrical problem, because Bluck (1967) produced considerable evidence of the common behavioural properties and spatial location of (1) rods and spheres, and (2) blades and discs. The chosen sequence (blades, discs, rods and spheres) is a slight compromise that distinguishes between these two pairs of shapes, but makes the vertical sequence of shapes in the diagrams run in alphabetical order, so that it can be easily recalled. For purposes of identification Figures 6.19AA-QB are known as 'shape frequency' curves.

2. The percentage of blades, discs, rods and spheres recorded for each discrete unit were plotted without regard to the size-frequency distribution curve of the sample. Such graphs are shown in Figures 6.20AA-LJ, and they represent the second analytical method used by Bluck (1967). The vertical sequence is again in the same alphabetic order. For purposes of identification, these figures are known as shape-percent curves.

3. The change in mean MPS for an increase in particle size was plotted. Such graphs are shown in Figures 6.21AA-LJ.

4. The change in mean OPI for an increase in

particle size was plotted. Such figures are shown in Figures 6.22AA-LJ.

5. The change in mean surface roundness for an increase in particle size was plotted. Such graphs are shown in Figures 6.23AA-KC.

Three types of line were used in the construction of these diagrams. A solid (unbroken) line was used when a trend in the data was distinct enough to enable a line to be drawn through consecutive points. A dashed (broken) line was used when consecutive points were closely scattered about a distinct trend. A dotted line was used when consecutive points were widely scattered producing only a general trend. Figure 6.24 shows an example of how these lines were drawn.

Although some of the diagrams listed above have been constructed using the A and B-axis to represent particle size, those using the C-axis will be examined first. It should be noted that 1,036 individual samples were taken of beach material using the standard sampling method (Figures 6.11-6.18). Only 983 samples were used in the construction of the above diagrams because of the accidental non-inclusion of the second spring tide sample (24.11.77 for Gileston and 25.11.77 for Nash), plus a few other samples which were unavoidably 'lost'. Data from the full 1,036 samples were used in the statistical tests which will be described. It was considered that such data loss was not a significant problem.

One aspect which became clear as these diagrams were being drawn was that the proportion of different shapes found in different size ranges constantly changed as size increased. The same was true for MPS, OPI and roundness. This ability of the graphical approach to bring out important non-linear shape changes for changes in size was its one great advantage over such generalised statistics as the sample mean. The function of shape modes within the sample, as well as the whole size-frequency structure could be seen, when in most instances values such as the mean and standard deviation would have conveyed such little information as to have been of questionable use.

6.3 <u>GENERAL CHARACTERISTICS OF THE BEACH SEDIMENT</u> (Stage 1)

Because the C-axis was initially chosen as the principal size parameter, results using this axis are examined first.

1. <u>Shape-Frequency Curves</u> (Figs:6.19AA-AB): Standard sampled data illustrated the negatively skewed nature of coarse beach sediment (Folk and Ward, 1957). There was a strongly peaked mode and an extensive tail of coarse

fractions. Shape arrangement within the mode was also negatively skewed with blades and discs more prominent in the smaller, and rods and spheres in the larger sizes. The proportion of shapes within the total sample was: Blades=12%, Discs=37%, Rods=20% and Spheres 31%, and at the modal peak discs represented 47% of the material. Bluck (1967, p130) observed that, "Disc shaped fragments are by far the most abundant, and the highest percentage of discs is found in the size class which is the modal size class of the gravel". Given that Bluck (1967) was referring to grid-collected data, an examination of the shape proportions from grid data was relevant. These were: Blades=9%, Discs=35%, Rods=18% and Spheres=38%, and at the modal peak discs represented 37% of the material. It was clear from the outset that discs were not "by far the most abundant" in Lias beach sediment. In fact, most samples analysed produced shape proportions in which blades were the least common, rods the next least, while discs and spheres were variously the most common. It was the ratio of these last two shapes in a sample which proved the most valuable indicator of sediment type.

2. <u>Shape-Percent</u> <u>Curves</u> (Figs:6.20AA-AB): Both standard and grid data displayed four key elements. To the centre-left of the modal size peak blades and discs predominated, whereas to the centre-right rods and sphere were apparent in greater numbers. In the first part of the right-hand

tail, the proportion of discs initially increased. This was followed by an increase in spheres in the largest sizes.

3. MPS Curves (Figs:6.21AA-AB): These reflected the above changes with low values accompanying blade/disc abundance, and high values associated with rods and spheres.

4. OPI Curves (Figs:6.22AA-AB): The predominance of rods to the right of the mode was reflected in positive OPI values (prolate).

5. Roundness Curve (Fig:6.23AA): Since no roundness values were gathered for grid data, roundness trends were limited to standard data. A peak in roundness scores was associated with material in the mode. This was presumably a result of the relative mobility of these sizes.

6.4 DIFFERENCES IN SEDIMENT FROM EACH BEACH (Stage 2)

1. Shape-Frequency Curves (Figs:6.19AC-AF): Gileston standard sediment produced a more sharply peaked mode and less extensive tail in comparison with Nash sediment. Discs at the modal peak represented 46% and 40% of the material in Gileston and Nash sediments respectively. The equivalent figures for spheres were 16% and 33% respectively. This difference between relative importance

of the two principal shapes was made even more clear with the calculation of the overall shape proportions. For Gileston these were: Blades=14%, Discs=38%, Rods=21%, Spheres=27%. For Nash these were: Blades=9%, Discs=36%, Rods=20%, Spheres=35%.

Grid data produced some differences, the most apparent being the more pronounced tail in Gileston sediments. Spheres were more abundant on both beaches, but especially at Nash and this was later found to be a function of the position of the grid on this beach. The general modal peak of Nash sediment was strictly bi-modal with discs predominant in the smaller size peak, and spheres in the larger peak.

2. Shape-Percent Curves (Figs:6.20AC-AF): Results for standard and grid data showed no clear differences between the construction of the four elements observed earlier. The long tail found in standard Nash sediment produced a secondary peak of discs of lower and longer amplitude than in Gileston sediment. A high proportion of spheres in grid sediment from Nash was apparent in the mode.

3. MPS Curves (Figs:6.21AC-AF): Little additional information was apparent in these.

4. OPI Curves (Figs:6.22AC-AF): Grid data from Gileston

beach produced a double peak associated with the consecutive peaks of blades and rods apparent in the Shape-Percent Curves (Fig:6.20AD).

5. Roundness Curves (Figs:6.23AB-AC): These showed slight differences in that, while the peak in roundness scores coincided with the size mode in Nash sediment, it lay to the right of this position in Gileston sediment. In addition, the larger sized particles in the tail of Nash sediment produced consistently lower roundness values than for the equivalent material from Gileston.

There were, therefore, some minor differences between the two types of material, but each had essentially the same basic structure. Differences between grid and standard data were really a fraction of two things: (1) standard data included information from the ridge crest and shore platform not included in grid data, and (2) standard data was drawn from a far greater along-beach range which evened out local peculiarities. Grid data, which was made of four separate samples, will be examined in more detail later (section 6.9).

6.5 ALONG-BEACH SEDIMENT CHANGES (Stage 3)

Bluck (1967, p130) stated, "Only on one of the beaches studied is there an increase in the proportions of spherical and rod shaped fragments ... along the beach". Orford (1973), using trend surface analysis, found significant along-beach sediment variation, which gave rise to a modification of Bluck's model (section 1.8.7.). Orford (1978) used sediment data derived from only one cross-section so that along-beach variation was not further examined.

6.5.1 Statistical Evidence

The mean and standard deviation of A and C-axes together with MPS, OPI and roundness, were computed for each of the 1036 samples of standard sediment data. In addition, the whole numbers of blades, discs, rods and spheres present in each sample were also recorded. Only data gathered between 10.11.77 and 20.10.78 were used so that the maximum possible number of results from each sampling point was 24.

Statistically significant variations in these populations of means, standard deviations and whole numbers between different sample points along-beach were tested. Based on the Kolmorogov-Smirnov Two Sample Test for Small Numbers (Seigal, 1956), the test had a high power efficiency (about 90%) compared with the t test for small samples (<40). It was therefore very suitable for use in this context. In accordance with the testing procedure, cumulative frequency scores were initially computed for the two populations (of parameter means, standard deviations or whole numbers) to be tested together. To accomplish this, 30 equal discrete units across a range reflecting the complete spread of values to be tested, were selected, and the number of values falling into each unit was cumulated.

Figures 6.25A-B show two examples of how the test might distinguish between two cumulative curves. Figure 6.25A illustrates a significant deviation between the general values of the two curves (typified by a difference between the medians), although the spread of the two curves is comparable. Figure 6.25B illustrates a significant deviation between the spread of the two curves, although the medians are comparable. These are the two situations in which a significant result can arise from the use of the Kolmogorov-Smirnov Test, although the exact situation in which this might occur can only be ascertained from drawing the cumulative curves.

Figure 6.26 shows an example of a result matrix obtained using the 24 whole number disc scores calculated for each point A sample on cross-sections 1-4 on Gileston beach. Differences between samples are shown at $P \leqslant 0.01$. This same test was carried out for all parameters and for all sample points (A,B,C1,D,E) except C2. This latter was not included because the sample number was sometimes too low. This test could show if sample parameter values obtained throughout the monitoring period differed from one sampling point to another. They could differ in terms of their general value, or spread, as shown in Figures 6.25A-B. It was justifiable, in this comparison of relative differences, to use sample means and standard deviations, notwithstanding earlier criticism of their weakness in conveying sedimentological information (section 3.4.2.).

Tables 6.1 and 6.2 present the results for Gileston and Nash sediments respectively. Figure 6.26 shows that six tests were undertaken for each sampling point. Of the 360 individual tests, making up 60 result matrices, for five sampling points and 12 parameters, Table 6.1 shows that 32% returned significant results. The equivalent figure for Nash was 38% (Table 6.2). (There was no sample point E on cross-section 4 at Nash because the platform remained bare; thus only 324 individual tests were undertaken). 91% of significant results were established at $p \leqslant 0.01$. If 32% and 38% seem to be low values, it should be remembered that at $p \leqslant 0.01$ only 1% of significant results would have been expected due to chance.

The first six parameters which showed greatest variation along-beach have been indicated by small inset figures in Tables 6.1 and 6.2. For Gileston sediments, the number of discs and spheres found in each sample showed considerable variation, although neither shape scored highly for Nash. Instead it was the number blades and rods which showed most variation on this beach. C-axis means and standard deviations scored highly for both beaches, but highest for Nash. MPS was a discriminant of along-beach sediment change; this time more so for Gileston. Because of the significance of blades and rods, OPI means also proved significant for Nash. Whereas mean surface roundness scores produced only 17% of significant results for Gileston, this figure increased to 81% for Nash, representing the most variable parameter on that beach. Parameter means and standard deviations provided roughly similar percentage significances for Nash, while means were slightly more significant for Gileston.

The five sampling points tested showed approximately the same order (in terms of percentage significance for the sediment of each point) on both beaches. Sampling points D and E showed the greatest along-beach sediment variation; 50% of tests proving significant for D at Gileston, and 47% of tests proving significant for E at Nash. Points A, B, and C1 produced roughly similar results for each beach (with the exception, perhaps, of A at Nash). However the average for these three points was 33% for Nash, compared with only 25% for Gileston.

Further information was obtained about results for the four Zingg shapes. Cumulative curves were drawn using data from the Kolmorogov-Smirnov Test, and where significant results were apparent, these were classified in two ways:

1. Differences between median values were noted (Fig:6.25A) in terms of whether that of the higher numbered cross-section was higher or lower than that of the one against which it was being compared. Reference to Figures 5.7. and 5.8. explains how this approach was designed to identify increases or decreases in the proportion of different shapes in sediment samples taken progressively further east along the beaches (i.e. in the direction of longshore drift). A median representing a higher number of spheres, for instance, from point D on cross-section 3, compared with that for point D on cross-section 1 at Gileston, would indicate an increase in the proportion of spheres to the east. A lower median value for 3 compared with 1, would indicate a decrease.

2. Differences between the spread of values were noted (Fig:6.25B) in terms of whether sediments from the highest numbered cross-section were more spread or less spread than those from the one against which it was being compared. This was designed to identify whether variations in the proportions of different shapes in

sediment, found during consecutive samples (i.e. over time), became greater or less to the east. This approach was adopted to see if the resorting of shapes into widely differing sub-facies occurred more often at different along-beach locations.

The difficulty with both these classification systems was that only obvious differences between medians or spreads were classified as increasing or decreasing in one direction or another. There were many occasions (38%) when the differences were not considered significant enough (particularly in terms of the spread) to classify, and this meant that the method was essentially subjective. Nevertheless, results are shown in Tables 6.3 and 6.4 for Gileston and Nash sediments respectively. For Gileston the most important result was that the proportion of discs increased, while the proportion of spheres decreased, between cross-sections 1 and 4 (Fig:5.8). However, 70% of the increase in discs and 50% of the decrease in spheres was associated with sample points A and E, which were not located on the active beach face. Examination of differences in spread proved negative.

For Nash (Table 6.4), a decrease in blades and rods was observed, together with an increase in spheres. These tendencies were more evenly spread across the five sampling locations. In addition, examination of differences in spread suggested that it decreased progressively between cross-sections 1 and 4 (Figure 5.7). Therefore sediments to the east were probably more stable in terms of their sub-facies structure over time.

6.5.2 Graphical Evidence

6.5.2.1 Gileston Beach

1. Shape-Frequency Curves (Figs:6.19AG-BB): These showed a number of similarities. Blades and discs were prominent to the centre-left of the modal peak in all four diagrams, with spheres and rods commoner on the righthand side. Sediments from cross-section 3 were most acutely peaked, and the width of the tail shortened progressively between cross-sections 1-4.

2. Shape-Percent Curves (Figs:6.20AG-AJ): Although these produced no clear evidence of progressive along-beach changes in the proportions of discs and spheres, identified by the statistical results, slight differences in the construction of these diagrams probably reflect along-beach sediment variation. A noticable fall in the proportion of spheres in tail sediments from cross-section 1 to 3 (Figure 5.8) could be seen. Spheres still played a prominent part in the extreme sizes, however.

3. MPS Curves (Figs:6.21AG-AJ): These were essentially similar.

4. OPI Curves (Figs:6.22AG-AJ): No significant differences could be observed.

6.5.2.2 Nash Beach

1. Shape-Frequency Curves (Figs:6.19BC-BF): These produced a contrast to the results for Gileston sediments. There was a clear and progressive along-beach variation in sediment structure. The modal size peak became steadily more peaked between cross-sections 1 and 4 (Fig:5.7). Extensive, polymodal tails from cross-sections 1 and 2, became reduced in sediments from 3, and were only vestigally developed in those from 4.

2. Shape-Percent Curves (Figs:6.20BA-BD): These showed a distinct, progressive reduction in the percentage of discs in the tails, between cross-sections 1 and 4 (Fig:5.7). This was compensated by an increase in spheres. This confirmed statistical evidence, and suggested that these along-beach differences might be associated with the larger size fraction.

3. MPS Curves (Figs:6.21BA-BD): The trends of these curves

were approximately similar, but absolute values rose progressively eastwards in the direction of longshore drift.

4. OPI Curves (Figs:6.22BA-BD): These approximated one another although fluctuations in the blade and rod content from cross-sections 1,2 and 3 caused minor variations in OPI scores.

5. Roundness Curves (Figs:6.23AH-BA): Absolute values increased dramatically between cross-sections 1 and 4 (eastwards), and explained why this parameter was such a powerful discriminant in statistical tests (Table 6.2).

6.5.3 Photographic Evidence

Statistically and graphically derived results suggested the existence of some along-beach changes in sediment composition on both beaches. It appeared that this was most pronounced on Nash beach; confirmation of which could be obtained from photographic evidence. Plates 10-13 show the beach at cross-sections 1-4 at Gileston respectively. They suggest the same general spatial distribution of size fractions down each cross-section. Plates 14-17 show the beach at cross-sections 1-4 at Nash. In contrast, these showed a marked change in particle size, size-range and surface roundness between cross-sections 1-4 (the latter nearest Nash Point). The actual level of along-beach sediment variation was therefore quite different on each beach.

6.6 <u>DOWN-BEACH</u> <u>SEDIMENT</u> <u>DIFFERENCES</u> (Stage 4)

Humbert (1968, p3) noted that, "....the observations of various authors on shape sorting across (down) the beach are in better accordance with each other than the results of studies regarding longshore sorting. Consequently, we may expect that changes in shape along-beach will probably be rather small compared to those across (down) it....". Bluck (1967) based his model upon evidence of down beach zonational changes found on several South Wales' beaches. Commenting on down-beach sub-facies divisions, Orford (1978, p 410) stated, "Despite these differences, what proves perplexing is that the basic realisation does not radically differ". He concluded (p412) that, "On a daily basis different profile configurations are realised superimposed on a basic facies set....". Therefore, it was likely that whatever daily fluctuations might have occurred in the detailed spatial arrangement of sub-facies on any of the cross-sections throughout the monitoring period, the basic zonational facies model, if present, should be apparent in the complete sequence of sediment data.

6.6.1 **Statistical Evidence**

The same statistical method mentioned previously (section 6.5.1) was used to identify possible down-beach variations in sediment composition. Figure 6.27 shows an example of the result matrix arrangement, indicating that 10 individual tests were carried out for each cross-section using each of the 12 parameters. 480 tests were undertaken for Gileston, compared with 432 for Nash (sample point E being absent on cross-section 4 of the latter beach).

Tables 6.5 and 6.6 present the results for Gileston and Nash beaches respectively. There was an immediate and profound difference to be seen between them. 54% of tests proved significant for Gileston sediments whereas only 23% proved significant for Nash. 93% of all significant results represented a confidence level of $p \leq 0.01$. Thus, down-beach sediment variation appeared more pronounced than along-beach variation at Gileston, in contrast to the dominance of along-beach variation at Nash. Down-beach variation recorded for Gileston was over twice as pronounced as that for Nash.

The six parameters which proved most successful discriminators of down-beach variation on each beach are again indicated by inset figures in the total's column of

Tables 6.5 and 6.6. C-axis standard deviations were most successful on both beaches, suggesting a considerable variation in size sorting (unimodal and non-unimodal) at different locations on the beach face. The numbers of spheres and discs found in samples from different locations were also important discriminators on both beaches. However, Nash sediments showed the importance of down-beach roundness and mean MPS variation, which were relatively undistinguished for Gileston. Instead, the number of blades in samples, and the value of OPI means, represented two of the top six discriminators for this latter beach. All 12 parameters returned higher percentage significances for Gileston sediments than was the case for Nash.

Cross-sections 1,2 and 4 on Gileston beach displayed relatively higher levels of down-beach sediment variation in comparison with cross-section 3. For Nash, differences between cross-sections were slight. However, results shown in the lower half of Table 6.8 suggested that the proportion of different shapes found in consecutive samples changed less towards the east on this beach.

A strong note of caution needs to be sounded about the influence of sediments from sample point E (beach platform) on these results. The righthand column of Tables 6.5 and 6.6 shows that on average no less than 50%

and 47% of significant results for Gileston and Nash beaches respectively, arose from the inclusion of E sediments in the tests. This meant that while the relative siginificance of down-beach variation for Gileston remained over double that for Nash, the absolute proportion of significant results for sample points A,B,C1 and D was only half of what it had been with the inclusion of E sediments (for both beaches). For these four points on Gileston, parameters which were good discriminators of this remaining variation became mean C-axis, C-axis standard deviation, the proportion of discs, the proporton of spheres, mean MPS and roundness standard deviation, in that order. The first four most important parameters remained the same, although their orders had changed.

All six parameters which proved best discriminators for Nash when E sediments were included, remained unchanged when they were removed. However, their order of importance became mean roundness, mean C-axis, C-axis standard deviation, the proportion of spheres, the proportion of discs and mean MPS. The six most important discriminators between E sediments and those from positions on the beach ridge face, are inset in the righthand columns of Tables 6.5. and 6.6.

What emerged from this important clarification was that E sediments on both beaches were strikingly different from those on the beach ridge face. Reference to Table 6.7, for Gileston beach, shows that E sediments contained a higher proportion of blades and a lower proportion of spheres, than other sediments on this beach. When figures from the rop right hand column of Table 6.7 were subtracted from the totals to the left, it became clear that sphere numbers increased while disc and rod numbers decreased down-beach between points A and D. Table 6.8 shows that E sediments for Nash did not differ so strikingly from those on the beach face, although they contained more blades and less discs, rods and spheres. As a result there was a striking increase in spheres and decrease in discs between sample points A and D on this beach.

Reference to the lower halves of Table 6.7 and 6.8 shows that for Gileston sediments the blade proportion present in E sediments changed relatively more over time (the spread is high) in comparison with sediments from other points, while the proportion of spheres remained relatively more constant. When figures for E sediments were removed from the totals, results indicated that the proportion of blades, rods and spheres found in samples from points A,B,C1 and D varied to a greater extent down-beach. Similar observations could be made for Nash E sediments, although removal of the figures for these sediments from totals in the lower half of Table 6.8

showed that the proportion of blades, discs and spheres found in beach face sediments became slightly more constant down-beach. Evidence for this, however, was based on relatively few results.

Complex though these results may appear, they did provide some insight into the down-beach arrangement of sediment on each beach. They suggested that down-beach variation was more pronounced than along-beach variation on Gileston beach, whereas along-beach variation was most pronounced on Nash beach. However, down-beach change became more muted if the rather extraordinary E sediments on both beaches were removed from the analysis. Particle size, and standard deviation (as a surrogate for sorting) produced the most striking variations. Roundness was again an important discriminant of change on Nash beach. The proportion of spheres and discs in sediment was also liable to change, this change increasing the former, while decreasing the latter down-beach.

6.6.2 **Graphical Evidence**

In his 1967 paper, Bluck stated (p130),

> "The most landward margins of all beach bars are composed of gravels which have a high proportion of discs shaped grains in the larger size classes,

spherical and rod shaped fragments being almost confined to the lower size ranges. Since the modal grain size of the sediment is lower than sizes in which there is a high proportion of discs, disc shaped fragments are not the most abundant variety in these gravels."

1. <u>Shape-Frequency Curves</u> (Figs:6.19BG-DB): These showed very little conformation to the Bluck sedimentation model. A sediments (ridge crest) did not display any of the criteria of Bluck's large disc zone; as outlined above. On the contrary, discs were confined to the lower particle sizes, and spheres to the higher sizes within the size mode. The six Gileston results (Figs:6.19BG-CD) showed that unimodal distributions of upper beach sediments were gradually contaminated by an increasingly pronounced tail of larger particles. E sediments were slightly different, with a highly sorted blade and disc mode, and a secondary mode of discs in larger sizes.

Results for Nash (Figs:6.19CE-DB) showed that the proportion of rods and spheres in the size mode increased steadily down-beach. These shapes accounted for 40% of the modal material at sample points A and B, over 50% at points C1 and C2, and approximately 60% at points D and E. Blades and discs were lost progressively to spheres until sample point E was reached, when spheres and discs were lost to rods and blades. This was therefore a contrast to Gileston sediments in which discs predominated in the mode at all sampling points.

2. Shape-Percent Curves (Figs:6.20BE-CF): In stark contrast to Bluck's large disc zone criteria, the A samples showed discs to be the predominant shape in the size mode. This was also true of B and C1 sediments on both beaches. Such material was not even comparable to the imbricate zone (section 1.7.3.2) because rods and spheres were very pronounced to the right of the mode. C2 and D sediments on both beaches could arguably have displayed infill zone characteristics (section 1.7.3.3), although material infilling the cobble/boulder frame (represented by the coarse tail) was as much made up of blades and discs, as rods and spheres.

3. MPS Curves (Figs:6.21BE-CF): While these were all similar for Nash, an increase in discs in the smaller tail sizes of D and E sediments for Gileston produced corresponding troughs in their MPS trends (Figs:6.21BI-BJ).

4. OPI Curves (Figs:6.22BE-CF): Increases in the proportion of blades and rods on the left of the size mode in Gileston D and E sediments gave rise to high (positive) OPI values (Figs:6.22BI-BJ). Proportionately higher

numbers of rods in the tails of Nash A and B sediments also caused OPI values to rise for these (Figs:6.22CA-CB).

5. <u>Roundness Curves</u> (Figs:6.23BB-CC): These showed little change between points A-C2 on Gileston beach; highest values being associated with modal sediments. These high values were associated with slightly larger particle sizes in D and E sediments (Figs:6.23BF-BG). Roundness curves displayed a gradual down-beach change on Nash beach. A double peak in A sediments gave way to a single peak in B,C1 and C2 sediments. D and E sediments showed little change within the size range. Roundness values were relatively higher for material in the size mode towards the top of the beach.

6.7 SIZE vs SHAPE RELATIONSHIPS

Although statistical evidence indicated some down-beach shape sorting of the kind observed by Bluck (1967), Orford (1978) and others, the graphical evidence was quite contrary to Bluck's (1967) zonational model. It became clear that the chosen size parameter (the C-axis) was having a profound effect on results. Just what this was, and what bearing it has on size-shape relationships, was to be discovered when some of the graphs were redrawn using both the A and B-axes. Figures 6.19IA-KF, 6.20GA-IB, 6.21GA-IB, 6.22GA-IB abd 6.23FA-GE show the results of

Shape-Frequency, Shape-Percent, MPS, OPI and Roundness for some of the samples already described, when the B-axis was used as the size parameter. Corresponding results using the A-axis are Figures 6.19PA-QB, 6.20LA-LJ, 6.21LA-LJ, 6.22LA-LJ and 6.23KA-KC. Before any of these is referred to in the text, the vital role of particle size on shape distribution, which was now clearly apparent, is described below.

6.7.1 Size / Shape Tendencies

The effect of using each of the three particle size parameters in turn to examine the shape structure of a particular sample can be explained by reference to the relationship between each axis and the four shapes involved. It is difficult to explain all the nuances of a trivariate system, such as three-dimensional shape classifications (Zingg, 1935, Sneed and Folk, 1958), when one variable is changed as the others remain constant. The easiest means by which such changes can be understood is by comparing the results using one axis with those of another.

Consequently, six diagrams have been drawn in Figures 6.28A-F, each illustrating the effect of recalculating a Shape-Frequency arrangement using one axis to represent size, by another. All six permutations using the three axes are covered by these. Figure 6.28A shows that use of the B-axis would rearrange results using the A such that rods (and to a lesser extent, blades), in which the B-axis is far smaller than the A, would tend to accumulate further to the left of the size-frequency curve. This would leave spheres and discs, in which the B-axis is relatively close to the A-axis, tending towards the larger sizes. Figure 6.28B shows how the opposite would be true if B-axis results were recalculated using the A-axis.

Figure 6.28C shows how those shapes in which the C-axis is significantly smaller than the A-axis (blades, discs and rods) would tend to be realised to the left of spheres, if A results were recalculated using C-axis for size. Of course the opposite would apply if C results were recalculated using the A-axis (Figure 6.28D). Figures 6.28E and F complete the sequence by showing how recalculating B results using the C-axis would realise discs (and to a lesser extent, blades), in which the C-axis is significantly smaller than the B, to the left of spheres and rods; the opposite being true of C results recalculated by the B-axis. It should be clear that for a given sample, each axis tends to rearrange shapes within the size-frequency curve in a unique way. In fact the size-frequency curve will also show subtle changes.

Although spheres, by definition, are the least altered by use of differing particle axes, the rearrangement of other shapes will alter the position at which a majority of spheres will be realised. Analysis by B-axis will favour the realisation of a majority of rods in the smaller sizes and discs in the higher sizes. Analysis by C-axis will favour the realisation of discs at lower, and spheres at higher sizes. Analysis by A-axis favours the realisation of spheres at lower, and other shapes at higher sizes.

6.7.2 Size vs Mean Shape

As a means of illustrating different size/shape tendencies produced from sediment samples when each axis is used to represent size, some of the samples already described were re-examined. This time mean A,B and C axes, calculated for particles falling into each 1cm unit between 0.1 and 49.9cm (0.1 and 99.9cm for the A-axis), were used to compute a Zingg shape (Appendix 6.2.). This mean shape acted as a general (though not exact) reflection of one shape's tendency to predominate over others as size increased. The results are schematically illustrated in Figures 6.29AA-EF, which for the purposes of identification are called Mean-Shape-Frequency diagrams.

Figures 6.29AA-EF are schematic in the sense that they simply show the arrangement of mean shapes within the size mode and the tail. No attempt was made to represent the actual size-frequency curve in any case. Shape-Frequency diagrams should be consulted for this information (Figures 6.19AA-QB). Instead particle size has been noted at key places along the horizontal axes (such as at the modal peak, the extremity of the tail, and at those points where there was a change in mean shape). No attempt was made at scaling along the axis so that the results remain simple and straightforward.

In an area under the size-frequency curve where one mean shape was completely dominant, the first letter of this shape has been printed in capitals. When two shapes were consecutively and equally realised, the first letters of these shapes have been printed in capitals separated by a comma. When one or more shapes were dominant, but one or more other shapes were also occasionally realised, the first are printed in capitals, with the minority printed in lower-case inside brackets.

Figures 6.29AA-AC indicate that (1) treatment by A-axis on all standard data realised spheres in the lowest sizes, discs with a few spheres within the mode, and discs, blades and rods across the tail; (2) treatment by B-axis realised rods in the smallest sizes, spheres with some discs within the mode, and mainly discs across the tail; (3) treatment by C-axis realised discs in the lowest sizes and within the mode, with spheres predominant across the tail. In this latter diagram even the secondary peak of discs in the tail, noted previously (section 6.3 and Fig:6.20AA), could be observed.

Further reference can be made to Mean-Shape-Frequency diagrams constructed for all grid data, and standard and grid data from the separate beaches (Figures 6.29AD-BF), and each time the tendencies illustrated in Figures 6.28A-F should be apparent to the eye. However, the real significance of this discovery becomes apparent if the down-beach variations in sediment composition, which were examined in section 6.6, are analysed using each axis and the Mean-Shape-Frequency approach.

Figures 6.29BG-BI show the results of using each axis on point A sediments from Gileston. The usual tendencies prevail. However, closer examination of the B-axis diagram (Fig:6.29BH) reveals an arrangement which almost perfectly fits Bluck's (1967) description of the large disc zone. Discs are found in the highest sizes and rods and spheres make up the size mode. Figures 6.29BJ-BL show the results for each axis on Gileston point B sediments. That for the B-axis (Fig:6.29BK) produces an arrangement indicative of Bluck's (1967) imbricate zone, in which discs are realised in abundance throughout the size-frequency curve; the largest number being found within the size mode. The tendency for this axis to realise rods in the lowest sizes is also apparent (Bluck refers to the existence of 'small' rods being trapped between imbricated discs - Bluck, 1967, p132). Figure 6.29BL (for the C-axis) shows the arrangement of shapes within the size mode noted on many occasions when this axis was used in the production of size-shape graphs (sections 6.3, 6.4, 6.5 and 6.6).

Figures 6.29CA-CC show the results for each axis on Gileston point C1 sediments. This time, that for the B-axis (Fig:6.29CB) is indicative of a transition between imbricate and infill zones. Discs are still realised within the size mode, but an increasingly well developed tail of coarse material is being infilled by rods, discs and spheres. By sample point C2 (Fig:6.29CE) the infill zone proper has been reached where a coarse tail is being infilled by rods and spheres. This arrangement is repeated for Gileston point D sediments using the B-axis (Fig:6.29CH). The importance of blades in Gileston point E sediments is indicated in all three diagrams (Figs:6.29CJ-CL). Thus Bluck's (1967) zonational model appears to be reliant upon use of the B-axis to represent size.

Examination of results for Nash sediment using the B-axis (Figs:6.29DB,DH,DK,EB and EE) produced results of large disc zone status for sample points A,B and C1. No imbricate zone appears present, for by point C2 the number of spheres and rods has increased to produce infill zone status. Such, too, is the nature of Nash point D sediments, while point E sediments produce an increase in 'small rods'. Absence of the imbricate zone in Nash sediments means that transition between large disc and infill zones is gradual, and, given that all six points have significant tails of coarse sediment (Figs:6.19KA-KF) which is being infilled by the modal sizes, they could all have come from the same zone, albeit with differing proportions of discs and spheres.

6.7.3 Discussion

Something of a contrast could be made between Nash and Gileston sediments in terms of their down-beach sedimentary structures, but the nature of this contrast seemed very much dependent upon the validity of using one or other of the three principal particle axes to derive results. In the sense that a more sharply defined zonational structure was apparent on Gileston rather than Nash beach, it could be said that mean shape evidence corroborated results produced by statistical analysis. Interpreting the nature of this structure on either beach was not necessarily straightforward. The Bluck (1967) and Orford (1978) models, based as they were on the concepts of shape sorting first observed by Cornish (1898b) and others, seemed to suggest the validity of results gleaned by the use of the B-axis. But there was no intrinsic reason why this axis should represent size any better than either of the other two. For this reason, the term 'large' in 'large disc zone' appeared to be a direct product of the use of B-axis values in size/shape diagrams.

There seemed no reason to suggest that certain shapes in the so-called large disc zone were especially confined to certain sizes. By using the B-axis, discs were large and spheres were small. The opposite was found when the C-axis was used, and the A-axis produced a mixture of both shapes in the modal size range. One aspect of the Bluck (1967) model was dependent upon this size differential in the large disc zone. This was the size-selected vertical infiltering of particles into a 'reservoir' beneath the zone, and the subsequent sub-surface seaward transport of these to the base of the imbricate zone (Figure 1.5). According to Bluck (1967, p132),

> "The backwash of waves breaking on the porous frame (of the large disc zone) travels through the gravel, rather than on the gravel surface, and in its passage combs finer material seaward, the size and shape of which depend upon the size and geometry of the ground pore space: the gravel in the upper part of the beach therefore acts as a

sieve on the infiltering particles. Insufficient data are as yet available to describe fully the shape sorting mechanism taking place in this sieving process, but it is known that spherical particles, on some beaches at least, move more quickly through the pores than do other shapes. The large disc zones of these beaches have aprons of spherical pebbles which are interpreted as having moved through the cobble frame of the large disc zone."

Some experiments using painted pebbles were cited by Bluck (1967) but results were not presented in his paper. Vertical filtering of particles within the beach surface is not only a reasonable assertion, it is an obvious function of swash force and gravity interaction processes acting on large particles (bed load). Such a physical response mechanism has been proposed as a major influence in tracer studies (Figure 4.12). But the question of pore-regulated shape selection in this process, and the subsequent sub-surface lateral seaward transport of material so removed, is not so straightforward. Although the modified Moss (1962, 1963) sediment selection model proposed in Chapter 4 recognized the importance of inter-particle pore space in determining depositional possibilities within the developing sediment, size as well as shape is considered an important aspect of deposition. In addition, it is implicitly recognized that once particles have become incorporated in sediments below the traction carpet, no further transport is envisaged until hydraulic forces operating from above increase in energy and exhume them once again.

Orford (1978, p411) also appeared sceptical about the potential of sub-surface loss to radically alter facies realisations:

> "On a deductive basis, the likelihood of facies stability is high, and there is little room for sediments to maneouver on the profile to avoid being realised in any given type....(one) possibility of sediment loss is burial at mid beach position, but as the observed thickness of sediment at this position is low, the likelihood of complete facies burial is limited."

Nevertheless, it is in terms of potential vertical filtering that the validity of using B-axis derived results might be enhanced. Susceptibility of the C-axis to swash backwash movement has been put down to the preferred settling orientation of particles (Krumbein, 1942; Albertson, 1953; Williams and Gulbrandsen, 1977) which brings them to rest on their maximum projection surfaces (A x B). This leaves the C-axis directly exposed to sub-horizontal entrainment flow-forces of swash and backwash. Blades and discs, with their relatively small C-axes, would be more likely to come to rest in this orientation. 'Larger' particles in the resulting framework would therefore be those possessing larger A or B axes. At the same time, the B-axes of relatively smaller particles would determine their ability to fall between larger clasts (just as the B-axes of sand grains determines the sieve size in which they are eventually trapped). Rods and spheres may then be more likely to fall between discs and blades. In this context, the biases revealed in B-axis shape/size diagrams maybe of relevant interest.

Size (and therefore mass) is also a crucial factor influencing depositional processes. Evidence has already been cited (Jolliffe, 1964, p67) which relates particle size to the transportive power of sea waves:

> "....for a particular size of wave, there is a particular size of material which moves at the greatest rate. As the waves become higher the size of material that travels most rapidly also increases. In general, the larger waves move the largest material most rapidly; smaller waves move the smaller particles most rapidly; while very

small waves may move only the smallest beach particles, the larger particles remaining more or less stationary."

It is suggested, therefore that on the beaches studied, where particle sizes vary considerably (with a range of over $10^4 cm^3$), that at certain times only certain sizes are genuinely active within the prevailing traction carpet. Among those that are active, shape-selection under certain conditions plays an important part in bringing shapes with a high pivotability (rods and spheres) down towards the beach toe and forcing oblate shapes (blades and discs) up the beach face. These processes may be more effective under mid to low energy conditions (Orford's (1978) post-storm swell and fairweather regimes - Table 1.2), when winnowing action below breaking waves and in backwash might loosen spherical and prolate material, allowing gravitational forces to assist its seaward transport. Coincident with this, turbulence of plunging breakers and leading swash edge might faciliate oblate particle entrainment, throwing such material landwards. Under these constructional conditions berm related disc imbrication and lower beach prolate/spherical infill should be enhanced in active particle sizes.

At higher wave energies (storm conditions) particle mass, rather than shape might play a more important part in swash/backwash entrainment. Spherical and prolate material along with oblate might be flung landwards in the turbulent swash edge (perhaps under the potential constructional forces observed by Orford (1977)), while equally less shape-discerning undertow forces, associated with the high phase-differences of short period storm waves (Kemp, 1960), might pull material down-beach for incorporation into the storm bar. Naturally, zonational division between oblate and prolate/spherical materials, established under lower energy conditions, would have an influence on the material available to entrainment process at any point. Thus a predominance of blades and discs around the beach crest (such as the point B sampling position on Gileston beach) would ensure the prospect of these shapes being realised in beach top storm facies, although mixed more generally with other shapes. On the same basis, a predominance of prolate/spherical material at lower beach positions would ensure their strong representation in storm bar facies. But particle size rather than shape would determine entrainment and transport rates during storm conditions, making storm conditions less clearly zonational in structure.

This could explain the mixed nature (shapes of approximately the same mass with different shapes) of sediments showing 'large disc zone' characteristics using B-axis shape/size results (Gileston point A, Nash point

A,B and C1 sediments). Largely a product of high energy conditions, shape sorting was not strongly developed within the mode of mobile material. When lower energy constructional processes enabled more discrete shape sorting to take place, upper beach disc predomination (recorded in Gileston point B sediments) together with prolate/spherical infill of the lower beach area (point C2 and D sediments from Gileston and Nash) could be seen in the modes.

Given that a variety of different depositional conditions must have prevailed on both beaches during the monitoring period, many interesting deviations from this generalised model may be obscurred in the 12 month's data. Morphological evidence suggested that at Nash, in particular, depositional conditions changed quite regularly, producing berms at a wide range of beach face locations (Chapter 5). Added to this was the fact that the standard sampling system did not ensure continuous sampling from specific morphological positions. C1 and C2 samples were taken from especially variable physical locations such as berm crests, faces or bases, or even where no berm was developed at all (Figures 6.3 to 6.10). B and D samples were also prone to these inconsistencies. Therefore, as a means of unravelling some of the sedimentary characteristics of beach morphology, sediment samples were carefully regrouped.

6.8. **BEACH SEDIMENT STRUCTURE AND MORPHOLOGY** (Stage 5)

6.8.1 **Selection of Sediment Samples**

It was evident from the results of Chapter 5 that significant changes in the morphology of all cross-sections on both beaches were recorded throughout the monitoring period. Although down-beach changes in surface sediment structure were observed simply by comparing all samples collected from the standard sampling positions, it was thought that more specific sub-facies should be identifiable from samples taken from particular morphological positions.

Orford's (1978) statistical analysis revealed 11 sub-facies whose down-beach realisation and arrangement gave rise to 5 facies types (Fig:1.8). In linking these to beach morphology, Orford considered the beach face as one complete unit, along the lines followed in the classification of profiles in Chapter 5 of this thesis. Thus all samples drawn from a step, bar or composite profile were linked to their respective morphologies.

Instead of doing likewise, using the 10 configuration type classification established in Chapter 5, this author decided to adopt a less strict approach in which samples were selected in terms of more localised beach face constructions, of which the most important were berms. It was felt that this would complement the profile classification procedure and display its relevance, if any, to facies type. Eight specific morphological locations were defined along each cross-section from which sediments could be selected for analysis. This selection will be considered first, before results are given. The eight sediment types were:

1. Upper beach, berm top (UBBT)

The objective here was to examine sediments from the top surface of accreting upper beach berms. Samples were chosen from berms of reasonable proportions, the top surfaces of which represented points of recent deposition. This latter aspect was ascertained from a comparison between a relevant profile and its predecessor. Only if net deposition was recorded at the chosen location was the sample taken from it considered for analysis. On Gileston beach the development of this berm-type was confined to cross-sections 1 and 4 (Fig:5.8). Nine samples from cross-section 1 were selected because evidence suggested the upper beach berm on 4 was largely unaffected during the monitoring period. These chosen samples are indicated on Figure 6.30A.

The lower portion of Figure 6.30A (as well as Figs:6.30B-

H) provides some relevant environmental data. Row 12 shows tidal regime in terms of the semi-diurnal high water level recorded in metres above O.D. for Barry Dock (section 2.3). Row 20 shows significant wave height ($\overline{H}_3$), or the mean of the highest third of waves, recorded in metres above still water level by the HRS wave rider buoy A (Report no:Ex 994, Figures 2.13 and 2.14A-E). Row 11 indicates the occurrence of storm events as defined by the HRS Wave Climate Study (Report no: Ex 914) in which the wind speed threshold was set at 10 or more knots/sec. This relatively low limit was taken because of the difficulty of identifying small storms. The sector between 220° and 320° (true) represents winds from the west. Row 13 indicates similarly defined storm events caused by winds from the northeast. Row 9 shows the time of sampling; this being the point at which the lower apex of each inverted triangle touches the lower horizontal margin of the row. Rows 1-8 show the samples selected from each cross-section, and provides information about the profile classification and standard sampling position from which they were taken.

Gileston UBBT samples were taken from CCUB snd CCCB profile types (see Table 5.2 for definitions of profile abreviations) and point B and C1 sampling positions. The 26 Nash samples were almost exclusively point B samples from CCUB, CCCB, LUB or CCMB configurations. Two of the latter profile types were considered relevant because they included berms which had top surfaces extending into the upper beach zone, even though their seaward faces were situated in the middle of the beach. Samples were located at points on the beach face which tended to slope gently seawards at an average of 4.3°.

This type of sediment was considered typical of a constructional, step profile arrangement, formed from material which could be defined as Bluck's (1967) large disc zone. It can be seen from Figure 6.30A that there was no obvious seasonal pattern underlying the development of this sediment type, samples being drawn from a variety of cross-sections at a variety of times.

2. Upper beach, no berm (UBNB)

The objective here was to examine sediments from the same upper beach area on profiles showing no berm development. Figure 6.30B shows that sample selections were only made from CCNB or LNB profile types. Preference was given to samples located at points showing net erosion between surveys. All four cross-sections on Gileston contributed to the 28 samples. There was some difficulty, however, in that most point B samples on this beach came from the beach ridge crest, which remained largely unaffected throughout the year. Therefore certain point C1 samples were included in this category where they occurred on a CCNB or LNB profile type and lay near the point B sampling position (Figs:6.3-6.10).

Unlike the previous sediment type, there was a seasonal pattern in the occurrence of UBNB samples on Gileston beach. 75% of the total were gathered during and between the months of November 1977 and March 1978 (i.e. the winter months), which corresponded to the seasonal configuration pattern described in section 5.7.1. Similarly, the lack of a seasonal configuration pattern on Nash beach (section 5.7.2) was also reflected in the almost random seasonal distribution of the 20 UBNB samples from this beach. All samples on both beaches were located at steeply sloping points on the beach face, dipping seaward at an average angle of 18.7°. This type of sediment was considered typical of down-combed, erosional sequences affecting Bluck's (1976) large disc zone.

3. <u>Mid beach, berm top</u> (MBBT)

These sediments were taken from the top surface of accreting mid beach berms. Selection was based on the same definition of deposition used in regard to UBBT sediments. Figure 6.30C shows that of the 37 Gileston and 18 Nash samples, over 80% of each were gathered during or between April and October 1978 (i.e. the summer months).

Samples were mainly from point B, C1 and C2 locations on CCMB, LMB or CCCB profile types. They were also from near-horizontal surfaces, sloping seawards at an average angle of 1.0°. This type of sediment was considered typical of a constructional step profile arrangement, as it affected Bluck's (1967) imbricate zone.

4. Mid beach, berm face (MBBF)

The objective here was to examine sediments lying on or at the base of the seaward face of well-developed mid beach berms. Selected samples lay between two and eight metres seawards of the crests of such berms. Figure 6.30D shows there was no clear seasonal pattern, although a slight majority of samples were gathered during or after April 1978. Point C1 and C2 samples produced this sediment type, and profile configuration varied between CCUB, CCMB, CCCB, LUB, LMB and LCB types. CCUB and LUB types were only included when an upper beach berm had a seaward face extending out into the mid beach zone. The 21 Gileston and 31 Nash samples were taken from points which varied in angle, but sloped seawards at an average of 13.4°. This sediment type was considered typical of a constructional arrangement, and was selected for comparison with berm top sediments to see what differences, if any, could be identified.

5. Mid beach, no berm (MBNB)

Samples were selected from situations in which no berm was developed (CCNB or LNB profile types). Preference was given to samples from points showing net erosion between surveys. Figure 6.30E shows something of the seasonal pattern for Gileston samples noted previously for UBNB sediments (Fig:6.30B), whereas Nash samples were more randomly distributed. The 11 Gileston and 17 Nash samples all came from C1 or C2 sampling points which sloped seawards at an average angle of 9.9°. This sediment type was considered typical of an erosional sequence affecting Bluck's (1967) imbricate zone.

6. Lower beach; berm top (LBBT)

It was considered that sediments taken from this position should be typical of lower beach bars formed out of material from Bluck's (1967) infill zone. In reality it was difficult to determine whether the constructional deposit represented a storm bar or a swash berm. Samples were all from positions of net deposition. Figure 6.30F shows that there were relatively few examples of this sediment type, and that they were all from Nash. Point C1 and C2, but mainly D samples were selected from CCCB, CCLB, LMB, LCB or LLB configurations. Beach face sampling points sloped seawards at an average angle of 5.4°.

7. Lower beach, with berm (LBWB)

As Orford (1978) noted considerable sub-facies variation within the lower beach zone (six of his eleven sub-facies were to be found there), it was decided to examine these sediments in a variety of situations. It was hypothesized that samples from the lower beach of profiles including mid or upper beach berms (of reasonable proportions) would represent such sediments under generally constructional swash conditions. In these situations, selected samples were more often from points of net erosion, and sample points sloped seawards at an average angle of 6.8°. Figure 6.30G shows how 28 Gileston and 30 Nash point D samples were selected from CCUB, CCMB, CCCB, LUB or LMB profile types. 86% of Gileston samples were gathered during or after April 1978, although there was no seasonal pattern in the selection of Nash sediments.

8. Lower beach, no berm (LBNB)

In the absence of a large number of lower beach berms or bars, it was considered that samples taken from the lower beach zone of profiles on which no berm was developed, might best represent the potentially constructive sub-facies of this zone in down-combed sequencies. Most samples were selected from points showing net deposition, and these sloped seawards at an average angle of 6.0°.

Figure 6.30H shows 80% of Gileston samples were gathered before April 1978, whereas Nash samples were slightly more evenly distributed, with the bulk (65%) gathered during or after this month. All 19 Gileston and 17 Nash samples were from the D sampling point on CCNB or LNB profiles.

6.8.2. **Additional Preparation**

Having made the selection of samples making up the above eight sediment types, samples were pooled within each type along the following lines. Usually there were enough samples to justify pooling together all those from cross-section 1 and 2 on Gileston beach. The same was done for samples from cross-sections 3 and 4 on the same beach, as well as for those from 1 and 2, and 3 and 4 on Nash beach. For most of the eight sediment types this produced four pools of samples. Exceptions were UBBT and MBNB samples from Gileston, and LBBT samples from Nash. These were either too few in number, or only came from one or two of the four cross-sections.

There were three principal reasons for adopting this approach. (1) It helped reduce some of the complications which could have arisen from ignoring longshore variations in sediment composition, identified in differing degrees on both beaches (section 6.5). (2) It raised the total number of particles being examined from the potential number of 30 in each sample, to between 150 and 690 in pooled groups; the average number in each pooled group was 363. (3) It enabled some comparison to be made between samples taken from the same morphological location, but different cross-sections. Thus it provided some impression of the general applicability of specific results to modelling.

30% of all particles sampled by the standard method were used in this analysis; in 27 pooled groups. Each group was used to produce the five shape-size graphs (shape-frequency, shape-percent, MPS, OPI and surface roundness). Because of differences revealed by the use of one size parameter compared with another, these graphs were constructed using both the B and C-axes. These graphs are represented in Figures 6.19DC-GE, 6.19KG-OA, 6.20CG-FC, 6.20IC-KI, 6.21CG-FC, 6.21IC-KI, 6.22CG-FC, 6.22IC-KI, 6.23CD-EJ and 6.23GF-JB.

Two additional sources of information were assembled before the results were interpreted. (1) size-frequency curves were produced for each sample within a pooled group to see what contribution each made to the final result, and what similarity there was between each. For logistical reasons this was only done using C-axis as the size parameter. Results are not shown, but are referred to in the text. (2) Tables 6.9 and 6.10 were constructed to provide more detailed environmental data. It was not possible to obtain direct recordings of relevant wave data during the monitoring period. High water was usually between 500-700 hrs. It was noted (and subsequently proved - see Chapter 7) that wave patterns changed significantly within the nearshore zone during an ebb tidal cycle, particularly after sea level had fallen below the base of the pebble ridge. Inaccuracies would therefore have arisen if sea-state records had been taken during the sampling period; which usually took place between 1000-1600 hrs.

Rows 1 to 8 in Tables 6.9. and 6.10. give the number of hours when mean hourly wind speeds were $\geqslant$ 11 knots ($\geqslant$ Beaufort Force 4), in eight different compass directions, during a chosen period before sampling. The data were taken from some of the wind roses provided in Figures 6.31AA-FF. These wind roses were themselves constructed from data from Cardiff Wales' Airport Met. Office (section 2.4).

The 'spider's web' forming the centre of each rose was designed to ease visual interpretation. It acts partially as a compass. In addition, within each of the eight directional sectors the seven parallel lines correspond in width to columns making up the 'telescopic' petals of each rose. Wind speeds represented in the diagrams increase in velocity as the widths of the columns increase. The narrowest column represents the percentage occurrence of mean hourly wind speeds between 7-10 knots/sec (Force 3). Thereafter, each increase in width represents an increase of 1 force unit on the Beaufort Scale, until the widest column is reached which represents speeds $\geqslant$ Force 8 ($\geqslant$ 34 knots/sec).

Apart from the first two wind roses (Figures 6.31AA-AB) which show the annual percentage occurrence of winds from all directions during the monitoring period (8104 hrs) at two different scales, the sample times, indicated above each rose, were selected as follows. Since High Water only attains a significant height above O.D. in relation to the pebble ridges at Gileston and Nash typically three to five days either side of MHWS, wind roses were constructed for periods representing this period immediately before and after sampling. When sampling at Gileston and Nash did not take place on consecutive days, two pre-sampling wind roses have been constructed, covering the two different periods. When sampling took place several days after MHWS, a wind rose was constructed for the general period before sampling, but not after. In the absence of directly measured wave data, these wind roses represented the only indication of prevailing conditions. Naturally, they were not able to give more than a general picture, and were of no use in identifying the occurrence of swell conditions. Only data from pre-sampling wind roses were used in Tables 6.9 and 6.10.

On April 10th 1978, HRS wave-rider buoys A,B and C (of the Severn Estuary Wave Climate Study - section 2.4) started transmitting deep water wave heights and wave period data (Figures 2.14A-E, 2.15A-F and 2.16A-E). Using raw data from buoy A (Table A, HRS Report No:EX 887) mean significant wave height ($\bar{H}_3$) and mean wave period ($\bar{T}$) recorded at high water, immediately before sampling, was entered in Rows 9 and 10 respectively. Rows 11 and 12 of Tables 6.9 and 6.10 contain the same parameters recorded 24 hours previously, so that some impression could be gained of the constancy, diminuation or increase in incident wave energy immediately prior to sampling. The height of High Water in metres above O.D. before sampling is given in Row 13. Row 14 enables the date of sampling to be adduced in exactly the same way as for diagrams 6.30A-H. In two instances buoy A's record was missing and information from buoy B was used in its place. Two tables were produced because sampling took place on different days on each beach.

6.8.3 UBBT Sediments

1. C-Axis (a) Size-Frequency Distributions: Gileston samples were mainly unimodal, showing good sorting with

very few coarse tail elements. Samples from cross-sections 3 and 4 on Nash beach were also generally well-sorted and even more clearly unimodal. Those from the other two cross-sections on this beach varied from well-sorted unimodal to poorly sorted polymodal with extensive coarse fractions. (b) Shape-Frequency Curves (Figs:6.19DC-DE): These reflected the above tendencies, with 6.19DC and DE showing similarities and typical C-axis shape arrangements within the curves. (c) Shape Percent Curves (Figs:6.20CG-CI): These showed initial blade/disc dominance was followed by rod/sphere dominance. Figs:6.20CH and CI showed a decline in spheres in their tails. (d) MPS Curves (Figs:6.21CG-CI): Sphericity increased as spheres became dominant; thereafter the influence of less-spherical shapes in the tail of Figs:6.21CH and CI could be seen. (e) OPI Curves (Figs:6.22CG-CI): High values were associated with rod/sphere dominance. (f) Roundness Curves (Figs:6.23CD-CF): The trend undulated above 0.5 for Gileston sediments. Figs:6.23CE and CF for Nash displayed the along-shore change in roundness values noted previously.

2. B-Axis (a) Shape-Frequency Curves (Figs:6.19KG-LA): These showed a similar variation between pooled samples seen using the C-axis. Best sorted sediments were those from cross-sections 3 and 4 on Nash beach. (b) Shape-Percent Curves (Figs:6.20IC-IE): Discs were well

represented in all sizes and made up the largest shape proportion in all three pooled groups (38%-43%). Figs:6.20IC and IE showed that the proportion of spheres increased with size in contradiction to the criteria of Bluck's (1967) large disc zone. Discs were dominant in the tails of Figs:6.20IC and ID. (c) <u>MPS</u> <u>Curves</u> (Figs:6.21IC-IE): These provided little information. (d) <u>OPI</u> <u>Curves</u> (Figs:6.22IC-IE): High positive values were associated with a large proportion of rods in the lower sizes. These were followed by a fall to negative scores as discs became dominant in the tails. Rods also made some contribution to the very coarsest fractions. (e) <u>Roundness</u> <u>Curves</u> (Figs:6.23GF-GH): Only the results for cross-sections 3 and 4 on Nash beach showed a significant trend, this being a fall from high to low values with an increase in size.

3. <u>Environmental</u> <u>Data</u> An examination of any relationship between the occurrence of UBBT sediments and prevailing environmental conditions was not promising. Despite the detailed information contained in Tables 6.9 and 6.10, and in Fig:6.30A, the random spread of UBBT samples shown in the latter diagram did not suggest that a link with generalized environmental data would be possible. Because wave data only covered little over half the monitoring period, and given that this was for deep water conditions only, the initial potential with which it had been

regarded, in the absence of direct records, was not to be realised.

Even the relationship between wind and waves was not straight forward. For instance, the wind blew from the west at speeds $\geqslant 11$ knots for 50 hours prior to the second period of sediment sampling on Gileston beach in September 1978, producing a deep water $\overline{H}_3$ of just 0.2m (Table 6.9). However the earlier sampling period of the same month was preceeded by only 22 hours of the same kind of winds, and yet a deep water $\overline{H}_3$ of 1.3m was recorded by buoy A.

6.8.4 **UBNB Sediments**

1. C-Axis (a) Size-Frequency Distributions. These were clearly similar to those for UBBT sediments, being well sorted and unimodal. Exceptions were samples from cross-sections 1 and 2 on Nash beach which were mainly polymodal and contained large coarse fractions. (b) Shape-Frequency Curves (Figs:6.19DF-EA): UBNB sediments from Gileston appeared slightly better sorted than UBBT sediments. The opposite was true of UBNB sediments from cross-sections 1 and 2 on Nash beach. In all cases, the proportion of discs was higher in UBNB sediments, being between 40-47%. (c) Shape-Percent Curves (Figs:6.20CJ-DC): There was little discernable difference between results for UBNB and UBBT sediments. (d) MPS Curves (Figs:6.21CJ-DC): Little

differece here also. (e) OPI Curves (Figs:6.22CJ-DC): These indicated a slight increase in discs in the lower sizes. (f) Roundness Curves (Figs:6.23CG-CJ): Both diagrams for Gileston sediments, and that for sediments from cross-sections 3 and 4 on Nash beach, showed roundness fell as size increased.

2. B-Axis (a) Shape-Frequency Curves (Figs:6.19LB-LE): UBNB sediments from Gileston seemed better sorted than UBBT sediments, with discs well represented in the mode. (b) Shape-Percent Curves (Figs:6.20IF-II): Some differences were apparent in Gileston sediments. Those from cross-sections 1 and 2 showed a general increase in the proportion of spheres as size increased, except in the very largest sizes. Those from cross-sections 3 and 4 showed high proportions of discs in all but the very smallest sizes. As such these latter sediments appeared to fulfill the criteria of Bluck's imbricate zone. Sediments from cross-sections 3 and 4 on Nash beach, on the other hand, produced results indicative of Bluck's large disc zone. UBNB and UBBT sediments from cross-sections 1 and 2 on Nash beach looked very similar, with the former containing fractionally more spheres in larger sizes. (c) MPS Curves (Figs:6.21IF-II): The differences between UBNB sediments from Gileston noted above could also be seen in these diagrams. Relative proportions of spheres and discs in each pooled group gave rise to trend

wave patterns out of phase with each other. (d) OPI Curves (Figs:6.22IF-II): Again, starkly different curves for Gileston sediment reflected the relative influence of discs. The predominance of discs in large sizes also affected results for cross-sections 3 and 4 on Nash. (e) Roundness Curves (Figs:6.23GI-HB): These showed no great differences between results for UBNB and UBBT sediments.

3. Environmental Data Since there was some seasonal pattern in the occurrence of UBNB sediments on Gileston beach, it was feasible to associate the high proportion of winter samples with relatively high spring tides and common westerly winds; although 113 hours of westerlies prior to the last sediment sample in March produced CCMB profile types (Table 6.9 and Figure 6.35C). Those UBNB samples from Gileston gathered during or after April 1978 coincided, more often than not, with the occurrence of relatively high $\overline{H}_3$ values (Figure 6.30B). It was, as always, difficult to observe any pattern in the occurrence of specific sediment types on Nash beach.

6.8.5 MBBT Sediments

1. C-Axis (a) Size-Frequency Distributions: Sediments from cross-sections 1 and 2 on Gileston, and 3 and 4 on Nash beach, gave rise to well sorted, unimodal distributions. The other two pooled groups contained polymodal samples

with large coarse fractions. (b) Shape-Frequency Curves (Figs:6.19EB-EE): The two best sorted groups had discs well represented in the modes (42-43% of sample). (c) Shape-Percent Curves (Figs:6.20DD-DG): These showed the usual C-axis controlled shape arrangements in all diagrams. (d) MPS Curves (Figs:6.21DD-DG): All except 6.21DD (which indicated that sphericity increased continuously with size) produced peak values in association with the dominance of spheres on the right hand side of the modal size peak. (e) OPI Curves (Figs:6.22DD-DG): All showed a slight increase in rods in the higher sizes. (f) Roundness Curves (Figs:6.23DA-DD): The best sorted groups (6.23DA and DD) showed roundness decreased steadily with size.

2. B-Axis (a)Shape-Frequency Curves (Figs:6.19LF-MA): Sediments from cross-sections 3 and 4 on Gileston beach were polymodal and poorly sorted. Although the same was true of those from 1 and 2 on Nash, the modal size peak was nevertheless clearly distinguishable. (b) Shape-Percent Curves (Figs:6.20IJ-JC): There was a noticeable similarity between 6.20IG and 6.20IJ, both showing imbricate zone status. As sediments making up these two diagrams were from distinctly different morphological positions on different cross-sections they suggested some independence between sediment structure and profile morphology. Sediments from cross-sections 3 and 4 on

Gileston produced an unusual structure which was reminiscent of a C-axis induced arrangement. Sediments from cross-sections 1 and 2 on Nash were suggestive of the imbricate zone, while those from 3 and 4 produced perfect evidence of Bluck's (1967) large disc zone. (c) MPS Curves (Figs:6.21IJ-JC): These added little extra information. (d) OPI Curves (Figs:6.22IJ-JC): These showed the influence of an increase in discs over rods in the larger sizes, although a corresponding increase in blades in the largest sizes of some groups disturbed the fall in OPI values. (e) Roundness Curves (Figs:6.23HC-HF): These provided little distinct information, except that the contrast between roundness values in the two pooled groups from Nash was not as great as might have been expected.

3. Environmental Data No discernable reason could be found for the seasonal distribution of MBBT sediments from Gileston beach. This approach was abandoned at this stage (see Chapter 7).

6.8.6 MBBF Sediments

1. C-Axis (a) Size-Frequency Distributions: With the exception of sediments from cross-sections 3 and 4 on Nash beach, most MBBF sediment samples were non-unimodal. Polymodality was most common, although bimodality was apparent in some cases. There was little continuity of

distribution type between samples. (b) Shape-Frequency Curves (Figs:6.19EF-FA): The first three diagrams in this sequence showed spheres and rods to be strongly represented to the right of the modal size peaks. In the case of sediments from cross-sections 3 and 4 on Gileston, and 1 and 2 on Nash beach, this peak was strictly bimodal with the smaller size mode coincident with disc predominance. Figure 6.19FA showed sediments to be better sorted.

(c) Shape-Percent Curves (Figs:6.20DH-EA): Little difference was immediately apparent betwen MBBT and MBBF sediments although a check of the whole number of particles of each shape making up the two sediment types revealed an average of 40% discs and 31% spheres in the former, and 33% discs and 42% spheres in the latter. This signified a clear change in sediment composition. Discs predominated on the crests, and spheres on the faces and bases of mid beach berms. (d) MPS Curves (Figs:6.21DH-EA): This influence of spheres, particularly within the modal size peaks of MBBF sediments, resulted in high sphericity scores (+0.75) being recorded. (e) OPI Curves (Figs:6.22DH-EA): Very little change between the proportions of blades and rods in MBBT and MBBF sediments meant that these curves were roughly comparable. (f) Roundness Curves (Figs:6.23DE-DH): These also showed little difference.

2. B-Axis (a) Shape-Frequency Curves (Figs:6.19MB-ME): These showed less clearly the characteristics illustrated by use of the C-axis. (b) Shape-Percent Curves (Figs:6.20JD-JG): As a result of an increase in spheres in MBBF sediments, this shape was well represented in both the modal size peaks and tails of all four diagrams. Evidence of Bluck's (1967) large disc and imbricate zones had disappeared, to be replaced by criteria indicative of the infill zone. Mean-Shape Curves constructed for these pooled groups (not shown) were similar to those shown in Figs:6.29CE and DH. (c) MPS Curves (Figs:6.21JD-JG): Higher sphericity values were generally obtained for MBBF sediments through the complete size range. (d) OPI Curves (Figs:6.22JD-JG): These were similar to those drawn using the C-axis in that little discernable difference between MBBT and MBBF types was distinguished. (e) Roundness Curves (Figs:6.23HG-HJ): There was some tendency for the large particle sizes to record lower roundness scores than was the case for MBBT sediments.

6.8.7 **MBNB Sediments**

1. C-Axis (a) Size-Frequency Distributions: The impression given by these was that sample distributions were primarily polymodal and similar to those of MBBF type. There were, however, a slightly larger number of unimodal distributions. (b) Shape-Frequency Curves (Figs:6.19FB-

FD): The great range of polymodal distributions shown by samples from cross-sections 1 and 2 on Nash beach gave rise to a complex arrangement, but it was still possible to distinguish disc and sphere dominated bimodality within a general size peak, similar to that shown by MBBF sediments. The results of MBNB and MBBF types were also similar for cross-sections 3 and 4 on this beach.

(c) Shape-Percent Curves (Figs:6.20EB-ED): MBNB and MBBF results were comparable for Gileston sediments. Results for Nash showed an increase in the proportion of discs in sediments from 1 and 2, and an increase in the proportion of spheres in sediments from 3 and 4. This was born out by an examination of the whole numbers of each shape making up each pooled group. Overall, the proportions were Blades:9%, Discs:34%, Rods:20% and Spheres:37%. As such these sediments were slightly more like the MBBF than MBBT type. (d) MPS Curves (Figs:6.21EB-ED): It was difficult to make such a distinction using this information. (e) OPI Curves (Figs:6.22EB-ED): It was also difficult to distinguish a generalised pattern with these. The contribution of blades and rods remained largely unchanged within MBBT, MBBF and MBNB sediment types. (f) Roundness Curves (Figs:6.23DI-EA): The only significant difference between mid beach types here was that MBNB sediments from cross-sections 3 and 4 on Nash beach did not display a straight forward linear relationship, suggesting a decrease in surface roundness for larger particles.

2. B-Axis (a) Shape-Frequency Curves (Figs:6.19MF-MH): Similar to MBBF results for the B-axis, these curves did not make the distinctions noted using the C-axis so clearly. (b) Shape-Percent Curves (Figs:6.20JH-JJ): MBNB results for Gileston were similar to those for MBBF. Cross-sections 1 and 2 on Nash beach produced results which, like MBBT sedimens from 3 and 4 on Gileston, were difficult to interpret. A high proportion of spheres in most sizes made MBNB and MBBF results for 3 and 4 at Nash comparable. The influence of using the B-axis could be seen in clustering discs on the right hand side of the modal size peaks of MBBF and MBNB types, although not as predominantly as at this point and in the tails of MBBT sediments. (c) MPS Curves (Figs:6.21JH-JJ): Little distinction could be made with these. (d) OPI Curves (Figs:6.22JH-JJ): In general MBNB curves for each pooled group were more like those of MBBF than MBBT, although distinctions were slight. (e) Roundness Curves (Figs:6.23IA-IC): Little information could be gleaned from these.

6.8.8 LBBT Sediments

1. C-Axis (a) Size-Frequency Distributions: In all but one case these were polymodal, often without a dominant

mode. Many showed extensive coarse fractions. (b) Shape-Frequency Curves (Fig:6.19FE): A dominant mode (strictly bimodal with alternate disc and sphere dominance) was seen when samples were pooled. There was also an extensive tail with sub-modal coarse fractions. (c) Shape-Percent Curves (Fig:6.20EE): This displayed the standard shape arrangement using the C-axis with an increase in blades and discs in the coarse fractions. (d) MPS Curve (Fig:6.21EE): This reflected the above observation. (e) OPI Curve (Fig:6.22EE): The initial part of the curve was similar to all mid beach type sediment results for cross-sections 1 and 2 for Nash beach (Figs:6.22DF, DJ and EC) in that it suggested the presence of two distinct populations of prolate material in mobile sizes in this area of the beach. The sensitivity of OPI Curves to slight changes in sediment structure made short period fluctuations difficult to interpret. (f) Roundness Curve (Fig:6.23EB): Highest values were associated with the mobile mode; thereafter roundness declined with size.

2. B-Axis (a) Shape-Frequency Curves (Fig:6.19NA): This displayed a sharper modal size peak than for the C-axis, with spheres well represented at its centre. (b) Shape-Percent Curves (Fig:6.20KA): Spheres were well represented in all sizes with the proportion of discs increasing in extreme sizes. (c) MPS Curve (Fig:6.21KA): This displayed little additional information. (d) OPI Curve (Fig:6.22KA):

An increase in rods within tail sediments was the only halt in a general decline in OPI values as size increased. (e) Roundness Curve (Fig:6.23ID): This showed a sinuous curve with two roundness peaks.

6.8.9 LBWB Sediments

1. C-Axis (a) Size-Frequency Distributions: These were commonly polymodal, sometimes with a clearly defined modal size peak, and at others with a wide range of sub-modes. Only samples from cross-section 4 on Nash beach produced any unimodal results. (b) Shape-Frequency Curves (Fig:6.19FF-GA): Sediments from cross-sections 1 and 2 on Gileston beach displayed a well sorted mode in mobile sizes, in which all shapes other than spheres were represented. Poorer sorting in this size range typified other sediments from this beach, although a mode of spheres was present. Sorting improved from west to east on Nash beach in these sediments. (c) Shape-Percent Curves (Figs:6.20EF-EI): The distinction between the two pooled groups from Gileston was also seen in an opposing arrangement of shapes to the right of the modal size peak in these diagrams. The two results from Nash matched this pattern. It appeared as if two different sediment structures could be realised from this sediment type. (d) MPS Curves (Figs:6.21EF-EI): No clear evidence of this dual arrangement could be seen in these diagrams. (e) OPI

Curves (Figs:6.22EF-EI): No pattern was to be observed in these either. (f) Roundness Curves (Figs:6.23EC-EF): It was of interest to note that the sharp decline in roundness values with an increase in size, displayed by some upper and mid beach pooled groups, was rarely to be found in lower beach sediments. Highest values were associated with more mobile particles, while tail sediments produced stable roundness scores around 0.5.

2. B-Axis (a) Shape-Frequency Curves (Figs:6.19NB-NE): Again, the distinction between well sorted and less well sorted size modes observed in results when using the C-axis, was not so clear to see using the B-axis. (b) Shape-Percent Curves (Figs:6.20KB-KE): The tendency, noted with C-axis results, for discs and spheres to alternately dominate the modes of the two Gileston pooled samples, was also apparent here. Nash results showed no such dichotomy, although the general contribution of spheres was high in each case, especially in sediments from cross-sections 3 and 4. The dominance of discs in the size mode of sediments from cross-sections 1 and 2 on Gileston beach was indicative of the imbricate zone. Imbricate material appeared to be infilling a coarse tail. (c) MPS Curves (Figs:6.21KB-KE): Opposing peaks and troughs at 10cm for the Gileston results underlined the observations made above. (d) OPI Curves (Figs:6.22KB-KE): The alternate peaks of rods and blades/discs seen in Shape-Percent

Curves gave rise to roughly comparable arrangements in all four OPI diagrams. (e) Roundness Curves (Figs:6.23IE-IH): These displayed little coherent pattern.

6.8.10 **LBNB Sediments**

1. C-Axis (a) Size-Frequency Distributions: These were similar to results for LBWB sediments. There were some examples of unimodality in samples from cross-section 4 on Nash beach. (b) Shape-Frequency Curves (Figs:6.19GB-GE): The first three diagrams in this sequence showed evidence of bimodality in smaller sizes. Each pooled group displayed the extensive tail of coarse fractions apparently typical of lower beach deposits. (c) Shape-Percent Curves (Figs:6.20EJ-FC): Unlike LBWB sediments these all produced comparable shape structures with customary C-axis blade/disc vs rod/sphere arrangement in the size mode, followed by a resurgence of discs in smaller tail sediments. An examination of the contribution made by each to the pooled groups of LBBT, LBWB and LBNB sediment types, showed the former to be richest in rods and spheres. The LBWB type was more similar to LBBT, and LBNB sediments were proportionately better endowed with discs. The average percentages were as follows (LBBT, LBWB and LBNB): Blades: 6,9,9, Discs:28,30,36, Rods: 25,21,18, Spheres: 41,40,37. These trends were representative of results from all pooled

groups. (d) MPS Curves (Figs:6.21EJ-FC): Highest values were associated with spheres to the right of the size mode and in the largest fractions. (e) OPI Curves (Figs:6.22EJ-FC): Highest scores in the small sizes indicated prolate fractions in Gileston sediments. Fluctuations were of a lower amplitude in Nash results. (f) Roundness Curves (Figs:6.23EG-EJ): Characteristically, little pattern was shown by these, except that the more mobile sediments recorded highest scores.

2. B-Axis (a) Shape-Frequency Curves (Figs:6.19NF-OA): These appeared comparable with results for LBWB. (b) Shape-Percent Curves (Figs:6.20KF-KI): These produced a confusing picture. It was likely that despite pooling, the sample size of 30 was less adequate for lower beach sediments because of their wide size range and distinct polymodality. Each LBNB pooled group showed a disc shape mode at some point to the right of the size mode, although the exact position varied. Spheres represented 50% of all LBNB sediments from cross-sections 3 and 4 on Nash beach. (c) MPS Curves (Figs:6.21KF-KI): Little pattern was displayed by these. (d) OPI Curves (Figs:6.22KF-KI): The disc modes mentioned above caused corresponding troughs in these curves. (e) Roundness Curves (Figs:6.23II-JB): Little coherent pattern was observed.

6.9 THE SCALE OF SEDIMENT VARIATION

The nature of along-beach and down-beach variation in sediment structure has been examined, and potential connections between the latter and detailed beach face morphological phenomenae sought. Variations during the monitoring period were obviously numerous in both principal directions. However, the need to cover a wide range of beach locations made it difficult to grasp the scale at which such variations could be expressed; with each cross-section over 400m apart it was virtually independent of changes occurring on others on the same beach. This had also proved a problem during an investigation of beach profiles (Chapter 5). Two spring-neap-spring continuous (daily) monitoring periods on each beach had been carried out, involving six closely spaced 'temporary' cross-sections, to indicate the scale at which significant morphological changes could be found. Similarly, two intense samples of sediment were carried out on each beach as a means of scaling surface sediment variations, during which another attempt to marry facies realisation to prevailing environmental conditions was made. This work formed Experiment 3, described in section 3.3.2, and was responsible for producing the grid sampled data, some aspects of which were described earlier in this chapter.

6.9.1 **Gileston Beach**

Figure 6.2 shows how a grid of 50 sampling points was set up on Gileston beach, using cross-section 4 as a base line. Figures 6.32A-H and 6.33A-H show results produced by a computer contouring program which modelled sediment variations on the beach face, based on the results of two independent samples. On each occasion 30 particles were sampled at each point, and the mean and standard deviation of five paramters (A, B and C-axis, MPS and OPI) computed. These values were used as basic data from which the contour plots were drawn. Plots showing A, B and C-axis data display contours in several centimetre intervals, whereas MPS and OPI plots display contours in the dimensionless units associated with these parameters. Horizontal (along-beach) and vertical (down-beach) axes (which were peculiar to the contouring program) are shown in metres. Positions within contoured plots are given in terms of the horizontal followed by the verical distances.

Plots are essentially plan-views of the beach face. The upper boundary lay near the beach ridge crest, and the lower boundary approximated the lower beach margin. The (down-beach) width of the beach face sampled was exactly 20 metres, and sample points were approximately 5m apart in the down-beach direction, and 30m apart along-beach. Despite problems associated with use of sample means and standard deviations, the fact that interest lay in relative differences between points rather than the representative nature of absolute quantities derived, made their use more acceptable.

1. 24th September 1979

This was a calm still day during which spring high tide (5.3m O.D. at Barry Dock) covered approximately three-quarters of the beach face. At 945 hrs breaker height was recorded at 15cm, wave period at 4 sec., and this produced small plunging breakers approaching from the south (normal to the shoreline). Figure 6.36A shows that winds had been predominantly westerly, with some strong winds from the southwest, during the preceeding month. Figure 6.36B confirmed that this westerly pattern had continued over the few days running up to spring tide. Figures 2.14-2.16 (analogue records from HRS wave rider buoys A, B and C) indicated relatively calm conditions for the 24th of September (Day 267). Buoy B recorded $\overline{H}_3$ = 0.31m and $\overline{T}$ = 3.6sec. However, on the previous day a complex low pressure system off Iceland, producing a trough extending to the southwest of England, had been responsible for triggering an HRS defined 'storm event' (section 6.8.1). During this, buoy B recorded $\overline{H}_3$ = 0.92m and $\overline{T}$ = 3.3sec. Beach profiles (Fig:6.2) were of various configurations. Profiles 1 and 7 were CCMB, 2 and 6 were CCUB, with the remainder recording no berm.

(a) Mean A, B and C Axes (Figs:6.32A-C): These showed a general increase in the size of material towards the ridge base. At one point (-260m, 25m) an area of smaller particles appeared to be infilling the coarse frame along the ridge base.

(b) Mean MPS and OPI (Figs:6.32D-E): Although sphericity also increased towards the base of the ridge, it seemed reasonably independent of size. The area of infill referred to above, for instance, was not identifiable, and the contour pattern differed significantly from those for size. The distribution of oblate material (negative values) and prolate material (positive values) was even more dramatically different. Some of the most oblate (disc like) particles were found in large particle sizes along the ridge base (-140m, 23m). Prolate (rod-like) material of smaller size, was recorded in the upper beach zone (0m, 17m and -200m, 20m).

(c) Standard Deviation of A and C-Axes (Figs:6.32F-G): With the exception of the area of lower beach infill, these diagrams showed that sample standard deviation of size (as a surrogate for size sorting) increased towards the ridge base.

(d) Standard Deviation of MPS (Fig:6.32H): This produced a more complex picture with high values at a variety of points along the pre-sampling high tide margin. None of the plots so far described provided any evidence associated with berm development, and this diagram was no exception.

2. 18th December 1979

In contrast to the previously described field-day, the 18th of December produced blustery, storm conditions. Although the tide was several days from spring (21st December), being only 4.9m O.D. at Barry Dock, the sea had covered almost the entire beach face prior to sampling. This must have been partially due to spilling southwesterly breakers which were noted (at 1000hrs) to be over 1m, in height, and to have a period of 6sec. Figures 6.36E shows that strong west and southwesterly winds had been recorded over the previous month, these prevailing right up to the time of sampling (Fig:6.36F). Figures 2.14-16 confirm that wave energy conditions had been high up to the 18th of December (Day 352). Days 347, 348, 349 and 351 had all produced HRS 'storm events', and on the field-day itself, buoy B recorded $\overline{H}_3$ = 1.95m and $\overline{T}$ = 5.9sec. The previous day a deep low pressure system moving east over northern Scotland, and a high pressure ridge between the Azores and southern Europe, had produced $\overline{H}_3$ = 2.47m and $\overline{T}$ = 5.9sec. for the same buoy. Profiles 3, 4 and 6 (Fig:6.2) were CCMB in configuration, 10 was CCUB, 9 was LLB, while the remaining five were without any berm.

(a) Mean A, B and C-Axes (Figs:6.33A-C): These plots showed a rearrangement of sediment structure such that along-beach variations were clearly visible. The area of lower beach infill had been removed and larger sized material was now exposed along the ridge base.

(b) Mean MPS and OPI (Figs:6.33D-E): Interestingly, the sphericity distribution showed some similarity with that of the previous beach sample (Fig:6.32D), although higher values were now realised at certain sampling points. Lower beach oblate material recorded at -140m, 20m in Figure 6.32E appeared to have been shifted up the beach to -150m, 18m (Fig:6.33E). The ridge of prolate material running from -30m, 25m to -100m, 10m in Figure 6.32E was clearly enhanced in Figure 6.33E.

(c) Standard Deviation of A and C-Axes (Figs:6.33F-G): The steady down-beach increase in standard deviation observed along the entire length of the sampling area in Figures 6.32F-G was now broken up (although not entirely destroyed) by 'islands' of high values (Fig:6.33F-G). These plots seemed to be a reflection of those of particle size (Figs:6.33A-C).

(d) Standard Deviation of MPS (Fig:6.33H): This showed considerable along-beach variation, and a quite different arrangement from Figure 6.32H.

3. Sample Composition

The two grid samples of 1500 particles were used to construct size/shape graphs as a means of comparing their total sediment structure.

(a) Shape-Frequency Curves (Figs:6.19GF-GG, IG-IH and PG-PH): The main difference between all these pairs was that the December sample produced a ploymodal tail. This was most probably associated with the exposure of larger lower beach material (Figs:6.33A-C). It was likely that each sub-mode within the tail represented a lower beach frame unit from a different location along-beach. These had apparently been exhumed from beneath infill material seemingly pushed up the beach face.

(b) Shape-Percent Curves (Figs:6.20FD-FE, GG-GH and LG-LH): Pairs of diagrams produced by B and C-axes were very similar to the overall proportion of shapes. That produced by the A-axis (6.20LG-LH) did suggest that a secondary peak of discs in the smaller tail sizes had been lost from December sediments.

(c) MPS Curves (Figs:6.21FD-FE, GG-GH and LG-LH): Those for B and C-axes suggested that the only change between the two samples was a general lowering of sphericity in the highest sizes. However, Figures 6.21LG-LH, for the A-axis, underlined again the influence of size on results, by producing the opposite trend.

(d) OPI Curves (Figs:6.22FD-FE, GG-GH and LG-LH): These pairs of diagrams all matched well, indicating little change. B-axis results (Figs:6.22GG-GH) produced a double peak of prolate material in the tail of December sediments. Figure 6.33E indicated that these peaks could have been associated with 'islands' of prolate material on the beach face.

The two facies, one apparently associated with low energy conditions, and the other with high energy, seemed to have been produced from virtually the same population of sediments. No 'reservoir' of hidden material had suddenly become available, although outer frame elements of cobbles and boulders seem to have been cleared of smaller infill, making them more apparent in December results. Although beach face morphology was typically variable on both occasions, the arrangement of sediment in December seemed constructional in origin, despite being associated with high energy conditions. It might therefore be classified as 'post-swell facies' according Orford's (1978) terminology (Table 1.2). The September arrangement, with its evidence of lower beach constructional prolate infill, was more likely to be a 'fairweather facies' (Table 1.2).

This comparative study was evidence of along and down-beach sediment variation on a scale which matched that found for beach face morphology (section 5.7.5). Unfortunately, there was little indication that a change in one was reflected in a change in the other. In some instances 'islands' of spherical, prolate or oblate material could be found in locations which defied the general shape-sorting model (section 1.7.2), although this model could be seen as a general rule. Smoother down-beach transitions in size and shape noted in September results were apparently 'broken up' in those for December. This made generalisation about facies response more problematic.

6.9.2 **Nash Beach**

Figure 6.1 shows how a similar grid of 50 sampling points was set up on Nash beach using cross-section 4 as a base line. Figures 6.34A-H and 6.35A-H show results of the contouring program on two samples taken from this beach. On these, the lower boundary approximated the lower beach margin, and the (down-beach) width was exactly 30m. Consequently the upper boundary ran seaward of the ridge crest along the cliff base. On the 8th of October 1979 high tide reached the cliff base, which has therefore been indicated by a broken line. Sample points were approximately 7.5m apart in the down-beach direction and 30m apart along-beach (Fig:6.1).

1. <u>8th October 1979</u>

Locally, winds were from the northwest and not especially strong. However, a fairly powerful southwesterly swell wave train was reaching the ridge crest at high tide. At 930hrs breaking wave height was 90cm and wave period 10sec. (by contrast, wave height at Gileston was little more than 15cm, highlighting the differing energy regimes on each beach). While waves were active over the beach face at Nash, breaker type was both spilling and plunging. In comparison with Figure 6.36A, 6.36C shows that the month prior to the Nash sample included a higher proportion of easterly winds. In fact winds from the east and the southwest were prevalent during the few days before sampling (Fig:6.36D). Although spring tide levels had been reached the previous day, on the 8th it stood at 6.2m O.D. at high tide in Barry Dock. Figures 2.14-2.16 did not suggest extreme wave conditions had recently been experienced, even though two days before the sampling (Day 279) a deep Low to the west of Ireland had been responsible for creating an HRS 'storm event' producing $\bar{H}_3$

= 0.54m and $\bar{T}$ = 3.4sec for buoy B. By Day 281, $\bar{H}_3$ had fallen to 0.47m, although, borne as they were on a high tide, this swell wave pattern had clearly affected the whole beach at Nash. Profiles 1,5 and 6 (Fig 6.1) were LLB in configuration, while all others produced no berm.

(a) Mean A, B and C-Axes (Figs:6.34A-C): Two cusps around the A and B sampling points on profiles 7 and 9 (Fig:6.1) produced areas of smaller particle size. These were bordered to seaward by a framework of cobbles and boulders extending up-beach in the horn between the cusps. An area around profiles 1-3 (Fig:6.1) was not so clearly defined in terms of particle size variation, there being a fairly even spread down the beach face.

(b) Mean MPS and OPI (Figs:6.34D-E): Material in the cusp centres produced relatively low sphericity values, although larger material along the beach toe and in the cusp horn was of variable sphericity. Highest scores were associated with less size-differentiated material around profiles 1-3 (Fig:6.1), which also indicated prolate characteristics. Upper and extreme lower beach material recorded disc-like properties. Elsewhere a band of prolate sediment was to be found around the mid-to-lower beach zone, approximating the position of those lower beach berms which were present.

(c) Standard Deviation of A and C-Axes (Figs:6.34F-G):

These produced interesting patterns showing that low values prevailed over most of the beach face. Higher values were clearly associated with the exposure of large material along the beach toe and cusp horn.

(d) Standard Deviation of MPS (Fig:6.34H): This suggested a gradual increase in the spread of MPS sample scores between profiles 1 to 10 (Fig:6.1). It produced an arrangement which like those for Gileston (Figs:6.32H and 6.33H) was quite different from any other. It seemed, however, that MPS standard deviations were higher in areas where the size gradient increased.

2. 2nd January 1980

This calm, clear winter's day belied the extreme conditions of the previous month. Tides were approaching spring levels, being 5.3m O.D. at high tide in Barry Dock. At 915hrs the 50cm breaking waves had a period of 5sec and were in plunging mode. Strong winds from all directions (but predominantly the west) during December (Fig:6.36G) had attenuated a few days prior to sampling (Fig:6.36H). Wave energy levels had also abated (Figs:2.14-2.16), buoy B recording $\overline{H}_3$= 0.23m and $\overline{T}$ = 4.1sec at 600hrs on Day 2, 1980. Conditions during December had produced no less than 10 HRS 'storm events', the last being on the 29th of December (Day 363) when a complex Low drifting from the north of Scotland into the North Sea caused buoy B to record $\overline{H}_3$ = 1.78m and $\overline{T}$ = 5.7sec, while strong winds blew from the west. Profiles 1,2,3 and 5 (Fig:6.1) displayed lower beach bars (LLB), while all others were without break of slope.

(a) Mean A,B and C-Axes (Figs:6.35A-C): These produced a much changed arrangement from that recorded in October (Figs:6.34A-C). No longer did size increase towards the ridge base, and it appeared that the more even arrangement observed around profiles 1-3 in October had been extended over most of the beach face. Several 'islands' of slightly higher particle size could be seen.

(b) Mean MPS and OPI (Figs:6.35D-E): The area of relatively low sphericity noted in October around the cusps (-260m, 25m) was still present. Over the remainder of the beach, sphericity values seemed slightly higher in January results. The low sphericity area appeared to contain disc-like material giving low OPI scores. Elsewhere, prolate material was often in greater abundance around the beach crest.

(c) Standard Deviation of A and C-Axes (Figs:6.35F-G): These diagrams reflected those for size, producing less extreme values and gradients than those for October (Figs:6.34F-G). As a first approximation, the surface sediment appeared generally well sorted.

(d) Standard Deviation of MPS (Fig:6.35H): Two 'islands' of high values associated with areas of high sphericity (Fig:6.35D) broke up a fairly even trend across the beach face.

3. Sample Composition

(a) Shape-Frequency Curves (Figs:6.19GF-HA, JA-JB and QA-QB): Unlike those produced by the two Gileston samples, these showed a significant change between October and January. The latter sediments had a reduced coarse tail and possessed a strongly size-sorted mode. This mode showed discs in the smaller sizes and spheres in the larger.

(b) Shape-Percent Curves (Figs:6.20FF-FG, GI,GJ and LI-LJ): Each showed the shape distribution tendencies associated with each particle axis. However, they all showed that January's results clearly contained a greater proportion of spheres within the mode. In the October sample shape breakdown was: Blades=8%, Discs=38%, Rods=14% and Spheres=39% (at the modal peak:3, 36, 12, 49). January's breakdown was Blades=6%, Discs=30%, Rods=16% and Spheres=46% (at the modal peak:4, 30, 6, 60). Thus an enhanced population of spheres in modal sizes had either been exhumed from, or brought into the area between October and January.

(c) MPS Curves (Figs:6.21FF-FG, GI-GJ and LI-LJ): These pairs of diagrams showed no remarkable differences except perhaps that larger sizes in January's sample had lower sphericities. However, the less extensive tail in these sediments meant that this observation was based on relatively few particles.

(d) OPI Curves (Figs:6.22FF-FG, GI-GJ and LI-LJ): Again these pairs showed little change except that the larger sizes in January's sample appeared more oblate.

Both these facies seemed to be associated with high energy conditions. That for October appeared to result from contemporaneous wave conditions, whereas evidence suggested January's arrangement was largely a product of storm force conditions at the end of December. Both appeared to be 'destructive' facies judging by the size and shape distribution and existence of some lower beach bars. October's results introduced the problem of rhythmic topography, in the form of beach cusps, which clearly influenced along-shore facies type. Prolate material in modal sizes had accumulated in the lower beach area, forming a break-point bar in some places. This had remained stranded as tide level receded over the shore platform. Constructive processes unleashed at the swash tip could have pushed this accumulation up-beach at a certain time during the ebbing cycle, leaving the outer frame of large boulders exposed. Although swell waves were held responsible for this arrangement, their size and breaker type could have been the cause of what seemed like net seaward particle transport. October's particle distribution therefore appeared a marginal storm facies.

January's sample, however, produced a result indicative of full storm conditions. Down-beach shape sorting was destroyed and much of the surface covered in a predominant population of spheres. This was very much in keeping with Bluck's (1967) own view of what he had termed 'Build up of the Beach Bar'.

> "On one occasion, after moderately rough seas, spherical particles were found blanketing the various zones already established on the beach. The paucity of disc shaped fragments in this blanketing deposit is believed to be due to the lack of discs on the seaward margin, from where the deposit had been derived, that is from the infill and outer frame zones."

Bluck (1967, p132)

Without prior knowledge of the pre-storm facies it was difficult to say from exactly where the influx of spheres in January's sample was derived. Not only could it have been spread out from a previous accumulation, as suggested by Bluck (1967), but specific hydraulic forces acting at a critical moment could have produced traction carpet conditions favouring the surface deposition of certain shapes and sizes from a range of material available within the active beach layer at all points. Evidence such as this underlined the need to examine prevailing hydraulic conditions more closely within the swash zone (Chapter 7).

6.10 DISCUSSION

It was clear from the presented results that Liassic limestone, from which both study beaches were almost exclusively derived, did not produce the same abundance of discs as were to be found on the beaches at Ogmore, Sker and Newton (Bluck, 1967) or even on Llanrhystyd beach (Orford, 1978). The availability of a labile subgreywacke on these latter four beaches was the main reason for this dominant disc phenomenon. Such material splits easily along its bedding planes. Bluck (1967) noted that disc or blade shaped particles were produced from spherical and rod shaped subgreywacke grains; weathering having opened planes of weakness so that on the slightest impact they broke into platy fragments. Limestone, on the other hand, being anisotropic, tended to break into more massive blocky fragments, increasing the proportion of spheres in resultant beach material. Therefore the proportion of discs and spheres, although jointly the most abundant shapes (>70%), were more finely balanced on Nash and Gileston beaches. Thus it appeared incorrect for Bluck (1967, p139) to write:

> "The relationship between shape and lithology....does not imply, at least on the beaches studied here, that the lithological composition of the source rock exerts any commanding influence over the shape composition of the beaches. Whether the beaches are backed by limestone (Cwm Nash) or boulder clay (Ogmore, Newtown and Sker) the same shape differentiation obtains. Surf action, with perhaps the exception of the iriable subgreywacke, does not so much make a shape....as use a shape already in existence, and in respect of the beaches studied here, the contributing areas have been sufficiently well endowed with all shapes as to permit a uniform type of shape differentiation on all of them."

The central question in determining the validity of this zonational model is concerned with the validity of the distinguishing criteria. Bluck's (1967) own analysis of

the overall shape breakdown of beach sediments (1967, Fig:2) clearly showed the B-axis tendency to realise rods in the smaller and discs in the larger sizes. Bluck (1967, p130) stated: "The reasons for these features are not yet understood". But part of the problem lay in Bluck's own misunderstanding of sediment transport processes on the beach face. As Orford (1978) (section 1.8.4) has already pointed out, beach sediment can be moved in both the onshore and offshore directions.
Bluck (1967) believed shape sorting during 'bar breakdown' was essentially the result of offshore particle movement. As a result Bluck (1967) referred to 'lag gravels' produced by "....spherical and rod shaped particles continuously moving seaward and discs tending to lag...." (1967, p133). This theme was reinforced by his concept of equilibrium: "Where the highest proportion of discs falls in a size grade which is the same as the modal size grade of the sediment, reworking is complete, and in that sense the sediment is in equilibrium with its new conditions" (1967, p137). This led directly from the proposal that, "Shape sorting is more selective in what it leaves behind than in what it removes..." (1967, p135).

Onshore movement of sediment is confined to what Bluck (1967) called 'build up of the bar'. In this there appears to be some contradiction in terms of the sorting mechanisms proposed. On the one hand, bar build up was directly associated with storm waves. On this aspect, Orford (1978, p20) was forced to admit: "Bluck's total incorporation of all material into a swash ridge under storm conditions is obviously not the same as the down-combing conditions experienced at Llanrhystyd under storm conditions." Nevertheless, Bluck (1967, p130) envisaged,

> "....that during storm conditions fragments of all shapes were thrown forward by waves, but discoidal particles being easily plucked from the sea floor; being lighter than, for example, a sphere of similar median diameter; and when in suspension having a lower settling velocity than any other shape....were larger than, or if the same size, thrown further than any other particle being moved by the wave. Conversely, the presence of large spherical shaped fragments at the foot of the bar may be partly due to their high settling velocity. During storm conditions, when moved, they were either smaller than or, if the same size, thrown a shorter distance than other shaped grains."

Thus shape sorting processes were associated with bar build up; a proposal agreed upon by Orford (1977) under certain storm conditions. However, bar breakdown, with its attendant production of lag gravel, is considered by Bluck (1967, p150) to take place from an 'initial' form which "....comprises a ridge of gravel positioned on or about the high tide mark....(which is)....composed of variously shaped fragments....". This difficulty arises essentially from an over emphasis upon the role of backwash in shape sorting processes. It is considered to be the main mechanism for shape selection. Depositional processes during backwash are far easier to observe (Bluck (1967) refers to them on many occasions) than are those which operate in the confused and turbulent waters of the swash. This emphasis upon backwash processes seems to have influenced Bluck's own terminology - 'breakdown', 'lag gravels', 'lateral filtering'. According to him (Bluck, 1967, p152):

> "Tractive transport on the beach is seen to take three forms: the most common is rolling, where the particle caught in the force of the backwash moves along the surface with which it is predominantly in contact. Disc shaped grains shuffle along, and some grains move collectively in a form known as surface creep."

The existence of these transportational processes is not disputed, but evidence presented in this thesis indicates that they are only part of a number of depositional phenomenae taking place under both swash and backwash. It is clear that shape sorting is present on all beaches studied by Bluck (1967), Orford (1978) and now the present author. To what extent it is the main factor determining particle movement is a matter for debate.

The tendency for different axes to realise differing shape arrangements using the size/shape approach has already been discussed (section 6.7.3). Reliance upon results using the B-axis to define Bluck's (1967) zonational model, although other axes produce different results, does not imply that those B-axis results are spurious. Indeed, the fact that larger numbers of rods and spheres have relatively smaller B-axes than discs in the 'large disc zone' is clearly substantiated by this present work. But it is a fact that there is no intrinsic reason why the B-axis is a better expression of particle size than any other axis. It is wishful thinking to believe otherwise. Thus in the case of the 'large disc zone', it is likely that in terms of particle mass (a most important factor governing transport potential) all shapes within the mode are roughly equivalent. In fact size-frequency diagrams have shown sediments of this zone to be well size sorted with a clearly defined mode.

With reference to the infill zone, although there appears to be a greater accumulation of spherical and prolate particles in the mode of these sediments, this does not imply that infilling of the outer frame is an exclusive perrogative of these two shapes. The existence of this zone is in least dispute. It does seem, however, that the tail of coarse material making up lower beach sediments on Gileston and Nash beaches (as well as that in the mode) is an order of magnitude larger than anything referred to by Bluck (1967). Results presented in Bluck's paper rarely include particle sizes greater than 9.5cm (95mm) B-axis. Figure 6.19IA shows this size to represent the modal peak of all Gileston and Nash sediment, and it is obvious that results would have been very different if sampling had been cut off at this point.

Figure 6.37 shows a diagram presented by Bluck (1967, Fig:27) of the depositional sequence below the infill zone on the beach at Cwm Nash (a pocket beach to the east of Nash Point - Fig:5.7). Despite the fact that material as large as 25cm B-axis is shown, inset 'shape-percent' diagrams are still cut off at 9.5cm. At the other end of the size spectrum, Bluck (1967) refers to little below 3.5cm (35mm), whereas samples from Gileston and Nash include material down to 0.4cm (lower boundary of the pebble category of the Wentworth Scale - Table 1). This greater range of scale is probably the main reason why certain criteria determining the existence of the 'outer cobble frame' were never met at Gileston and Nash. These are that the deposits should be the best sorted and have a generally positive skew. Given that infill material often had a modal size coincident with the highest proportion of spherical particles, this could have been considered the direct relation of Bluck's (1967) outer cobble frame as found on Ogmore, Newtown and Sker beaches.

Disc imbrication of the kind referred to by Bluck (1967) was not often seen in Gileston and Nash sediments, although disc accumulation was associated with berm development. Imbricate zone material, or simply disc-rich deposits, seemed to arise from two distinct processes. The first could be seen in the difference between UBBT and UBNB type sediments. Both were well size sorted, but the former with a general variety of shapes. The proportion of discs in UBNB sediments was slightly but significantly higher. This was probably a lag gravel produced by the sorting model favoured by Bluck (1967); the operation of which created imbricate zone sediments from a breakdown of the large disc zone. As an upper beach berm was combed down, discs had lagged, thus increasing their proportion in the remaining sediment by a few vital percent.

On the other hand, the even clearer distinction between MBBT and MBBF type deposits, in which modal disc domination of the former was replaced by modal sphere domination of the latter, indicated a 'constructional' form of shape sorting process. This took place at or near the swash tip; discs being thrown forward and spheres being rolled back or remaining in place to form the berm face or basal deposits. MBNB type material, originating from an erosional sequence, produced a shape breakdown more similar to the MBBF type, although with a slightly reduced proportion of spheres.

Lower beach deposits justified Orford's (1978) detailed assessment of their potential sub-facies arrangements, in being the most complex of all sediments. It is worth noting that Bluck's (1967) infill zone was also the most detailed in form. The modal percentage of spherical and prolate shapes was high in almost all samples taken from this area, although LBWB sediments from cross-sections 1 and 2 on Gileston beach indicated predominantly oblate fill. However, shape breakdown in the three lower beach depositional types suggested that infill increased the proportion of spheres, whereas erosion created a more equitable balance between principal shapes. The coarse tail which was present at all times, became more clearly defined with the the removal of infill.

There appear to be significant differences between the two beaches in terms of their composition and structure which indicate a differing origin. Gileston beach reflects many of the features described by Orford (1978) in the developmental history of the pebble beach at Llanrhystyd. Although, unlike Llanrhystyd, Gileston still receives a rich supply of fresh sediment from the west, it represents a fringing beach originating from the sweeping up of loose shelf sediment during the post-glacial rise in sea level. Many of the size and shape sorting processes apparent today were in operation as this barrier of coarse material was rolled onshore. In this process of ridge migration,

> "the outer cobble frame keeps to its lower beach position and trundles onshore in the wake of the migrating top beach ridge. Material that is too large for base beach entrainment is left exposed on the wave cut platform. Constant grinding in the outer frame keeps up the prolate tendency of material, while the rate of ridge migration dictates the amount of material left behind."
>
> (Orford, 1978, p414)

This can certainly be envisaged for boulder sized material fringing the beach toe, although evidence presented here suggests all shapes (except perhaps blades) are well represented in this deposit.

That wave energy levels much higher than those prevailing today, were responsible for emplacing the substantial beach ridge accumulation at Gileston, can be seen in the existence of rounder, more spherical material found to the rear of the present day beach in vestigal ridges, and in the core of the beach ridge itself (Fig:2.3). Although no rigorous sedimentological investigation was carried out on these deposits, they were strongly reminiscent of material from the eastern end of Nash beach where wave energy levels are typically high.

It is not clear, however, why present day sediments on Gileston beach contain a higher proportion of discs than found at Nash, but results have indicated the disc-rich deposits (associated with UBNB and MBBT type material) are more commonly realised on the former beach. At present, wave energy levels are lower on this beach (partially the result of the most recent post-glacial readjustment of land/sea level), leaving the beach well able to respond to most seas without major effect. At certain points, however, crestal overtopping can be seen to have occurred in the arrangement of back beach deposits. On one occasion (21st January 1980) the author observed a ridge of material up to 30cm in height being built along the beach crest during a half-hour period, when a local squall enhanced high seas on a spring tide to produce overtopping. The beach face itself was intensively down-combed.

The beach at Nash must have originated along the same lines as that at Gileston. At a certain time during the post-glacial, the migrating ridge came into contact with an old cliff line hewn in the Lias. From that time on the beach was significantly modified. Wave energy levels probably increased as sea level continued to rise. Material from the thoroughly unstable cliff strata produced a continual source of fresh supply. The dramatic tidal regime in the confines of the Bristol Channel, together with the predominance of westerly and southwesterly wave trains ensured that longshore movement was an important factor on both beaches. On Gileston its influence can be seen in the eastward decrease in extreme tail sediment sizes between cross-sections 1-4 (Fig:5.8), and in the existence of along-beach changes in sediment composition.

On Nash beach, however, the arrangement of sediments is dominated by this longshore drift of material. Fresh sediment is made available from cliff-falls along the entire length of the beach. However, the slight anticline between Nash and Monknash Points (Fig:5.7) which brings weaker angulata strata to the surface, is responsible for greater instability at the centre (around cross-section 1, Fig:5.7). Samples from this area have considerable tail populations, which, because of the shelter afforded by an offshore sand bank (Fig:2.1) are only gradually broken down by abrasion. During this process modal sizes increase in roundness and move with greater ease to the east where Nash Point, acting as a giant natural groyne, keeps it impounded. As a result, down-beach zonal development is over-ridden to a great extent by the availability of material in the along-beach direction.

With regard to the relative importance of particle shape and size in depostitional processes, it is proposed that despite evidence of shape sorting, particle size is equally, if not more important in determining sedimentological response to swash processes. Both Bluck (1967) and Orford (1978) geared their work to the identification of shape sorting. The same basic approach had been adopted by the present author. In each case evidence has been presented to confirm its existence, although its relative importance is still questionable. The small (but some might argue critical) changes in shape composition that could be identified on both Nash and Gileston beaches, suggest that shape is probably of secondary importance to mass in determining the erosional and depositional potential of particles. Shape selection is certainly a factor in both net onshore and offshore depositional sequences, but weaknesses in Bluck's (1967) 'large disc zone' criteria, for instance, imply that such sediment (often highly size sorted) is the product of less shape discriminating processes than was initially supposed.

It is further suggested that while shape selection can never be removed from the equation, there are times when it is of greater or lesser importance. When swash and/or backwash produce entrainment forces which are at the critical threshold for transport of certain particle sizes, more easily suspended oblate material is thrown forward during the short-lived energy peak of the swash. The longer duration, lower initial energy level of the backwash produces down-beach winnowing of spherical and prolate material, along lines proposed by Bluck (1967). This description typifies conditions during berm build up, and is a vital factor determining the relatively high degree of shape change between base, face and crest deposits. It can also create the winnowing of certain shapes down-beach in erosional sequences.

At times, when entrainment forces are no longer marginal, mass rather than shape is of greater importance in determining net up-beach or down-beach (or indeed along-beach) transport potential. That energy levels such as these are commonly met at Nash provides some explanation of the reduced level of zonational shape sorting found on this beach. Although examples of disc-rich deposits were found along cross-sections 1 and 2 (Fig:5.7), in association with the formation of berms, more abraded deposits near the headland often produced a smoother down-beach sequence in which a predominance of discs was replaced by a general increase in spheres. It is also proposed that the beach crest at Gileston is a product of high energy conditions, and that the selection of material is more seriously related to size than to shape.

It is worth noting that by a useful coincidence Carr (in prep.) has also been considering the relative merits of particle size and shape. In a paper presented to the Institute of Civil Engineers' Symposium on shoreline protection, Carr (pers. comm., 1982) has written: "The comparative unimportance of shape factors at Chesil is probably due to the rather limited range occuring there and the higher wave energy. It is noteworthy that not only Budleigh and Slapton, but many other beaches where shape-sorting has been described ....are in relatively low energy environments". Thus, the results presented here, and Carr's review of a decade's work are both pointing in the same direction. Shape and size are both important factors, the relative primacy of which is determined by the energy levels prevailing.

To some extent, Bluck (1967) can be said to have taken too strong a stance in his rejection of size (or mass) as an important despositional criterion. His understandable (and correct) dissatisfaction with mechanical analysis based on moment measures, which are seemingly of limited use in dealing with coarse sediment populations, led him to conclude:

"Whatever the ultimate cause may be of these changes in the statistical parameters associated with size sorting, it is evident that they are less useful in subdividing the beach bar than the shape/size procedure adopted here and elsewhere (Bluck, (1965); and since it is from an analysis of the beach bar zonal development that the mechanics of sediment movement is deduced, mechanical analysis can only be regarded as an inferior tool to the point of being supplementary."

(Bluck, 1967, p149).

On the basis of evidence presented in this thesis, this conclusion cannot be justified. It is true, however, that the size-shape-frequency approach produces a far greater appreciation of the total sample breakdown, both in terms of size and shape composition, than traditionl mechanical analysis. But additional difficulties associated with the choice of size parameter need also to be taken into account.

Some other observations can also be made. Evidence produced from contouring grid data has shown the small-scale sedimentological variations which can be produced by the same apparent conditions. As such, this corroborates the results of Chapter 5 regarding the variable nature of beach morpholgy. It has proved difficult to marry generalized environmental descriptors (such as deep water wave height and period) with depositional response, when this is neither morphologically nor sedimentologically uniform. This was partly due to the accuracy with which 'response' was measured in comparison with the generalities of 'process'.

It is clear that local conditions vary, not only between beaches, but also along the length of an individual beach. Wave refraction is largely responsible for this energy variation, the expression of which, for any given set of wave parameters, may also change during a single tidal cycle. The past history of an area of beach, in terms of its particle arrangement and profile, are also important factors determining likely response. Therefore the ability to measure with accuracy breaking wave and swash zone characteristics will be a vital step in establishing the reasons for specific types of beach response. In the natural environment, measurements such as these have been traditionally difficult to make, and are consequently few in number. The following chapter outlines a further attempt to develop this work.

The peculiarity of point E sediments, taken from the shore platform, have not been fully explained. To some extent these should be considered separately from those of the beach face; although their less distinctive nature on Nash beach suggests that they are partially toe sediments which for one reason or another have become detached from the ridge. But their high percentage of blades (and to a lesser extent, rods) results from their other source of supply - the platform surface itself. At Gileston in particular, where highly jointed upper bucklandi strata are being constantly undermined by marine abrasion, blade shaped fragments of low initial roundness are constantly being made available. Some of these particles do eventually become incorporated in lower beach D sediments.

Finally, with regard to certain parameters referred to in this thesis, MPS and OPI both provided useful additional information at times. Used in conjunction with the shape frequency and shape-percent curves, MPS tended to dampen changes in sediment composition. OPI, on the other hand, proved rather volatile to changes in the minor fractions (blades and rods). They were generally of secondary importance. Surface roundness, despite its less accurate method of determination, proved a useful discriminator of change at one level. However, there is an aspect of the roundness curves which has not yet been fully explained. Figures 6.23AA-KC are commonly sinuous in appearance. This suggests that certain sizes (and possibly shapes) were stable during periods in which abrasion improved their level of roundness. Breakage followed, causing roundness scores to slump sharply in smaller sizes. This in turn was followed by another period of relative stability and increasing roundness. No detailed work was carried out to determine whether breakage was associated with certain sizes or shapes, but the process itself was apparent in the results.

6.11 SUMMARY

A large quantity of sedimentological data derived from two types of sampling routine has been subjected to rigorous analysis based on the expression of size/shape relationships. These results, presented in graphical form, have provided evidence of size and shape sorting mechanisms operating on the two study beaches. The sediment on both beaches produced a rough balance between discs and spheres, which together made up over two thirds of all particle shapes. The ratio of discs against spheres proved a vital factor in the description of different sediment types. A proportionately greater number of discs were found in Gileston sediment but the reason for this was not known. Coarse material making up the tail of the size-frequency curve was more extensively developed in Nash sediments because of the source of fresh supply from cliff falls.

In contrast to Bluck's (1967) observations on adjacent beaches, evidence of significant along-beach variations in sediment composition has been presented, both in terms of statistical results and size/shape relationships. Both these indicated the importance of longshore drift on Nash beach, in particular. Such variation could most commonly be seen on both beaches in relation to particle size and size sorting, although surface roundness values also changed considerably along-beach at Nash.

Down-beach changes in sediment type were roughly comparable to along-beach variation on Gileston beach, whereas at Nash these changes were of secondary importance. Size/shape relationships using the C-axis to represent size, produced results quite contrary to those presented by Bluck (1967). It was apparent that the choice of size parameter was influencing results, and subsequent recalculation using both A and B-axes produced significantly different size/shape arrangements. It has been shown that each axis, when used in the graphical size/shape procedure, creates its own tendency to realise greater proportions of shapes at different points under the size-frequency curve. It is therefore necessary to follow Bluck's (1967) preference for the B-axis to obtain results indicative of his proposed zones. The validity of this approach has been questioned.

Eight distinct depositional types of sediment taken from different morphological locations on the beach profile, were selected as a means of identifying specific sub-facies. Using the size/shape approach based on both B and C-axes, shape selection has been associated with the deposition and erosion of berms. Disc-rich deposits can take a constructional form when laid down at the crest of a berm, or be formed as a lag sediment during the erosion of top-beach material. The arrangement of sediments on the lower beach appears more complex, although spherical and prolate particles were more commonly realised in material infilling the frame of cobbles and boulders. Attempts to link the derivation of these depositional types with generalised environmental conditions proved fruitless.

By concentrated and systematic sampling of a small area of beach face, contoured plots of sediment variation were produced. Using these to gain an appreciation of the scale of variation suggested non-uniform sediment response to prevailing conditions. It was just possible to generalise process/response conditions from environmental data. This work underlined the need for a means of accurately measuring swash zone processes, because it was clear that refraction controlled, along-beach variation in wave energy levels complicated predictions about facies response.

In reviewing the results of this comprehensive sedimentological investigation, it was possible to assess the validity of Bluck's (1967) shape sorting model. Bluck's (1967) emphasis on the role of backwash in shape sorting is held responsible for the derivation of a one-sided sedimentation system. Reliance upon B-axis results with their distinct size/shape tendencies appears to have led Bluck (1967) to reject particle mass as a factor in determining a particle's transportational and depositional potential. It has been proposed, on the basis of evidence presented here, that shape sorting, while an important process, is not necessarily the primary one responsible for pebble beach facies response. Particle size, or more accurately, its mass, has a vital role to play at times when swash zone entrainment forces greatly exceed transportational threshold levels for certain particle sizes. 'Constructive' and 'destructive' sediment sequences based more effectively on shape selection are considered the result of marginal entrainment force conditions. This is in agreement with the view of Carr (pers. comm., 1982).

Models for the genesis of Gileston and Nash beaches have been proposed. Both started from the same initial onshore migration of loose shelf sediment, upon which size and shape sorting mechanisms were imposed. The ridge of sediment from which the present day beach at Gileston is built, was able to roll onshore unimpeded, responding at all times to the influence of high wave energy conditions. It has subsequently evolved a stable relationship with the presently prevailing wave energy regime. Marginal entrainment conditions, referred to above, are more commonly encountered on this beach which consequently displays greater evidence of shape sorted deposits.

In contrast, the ridge of sediment which was to form the beach at Nash, came into contact with an old cliff line at a certain point during its post-glacial history, which impeded further migration. From this time onwards the beach became modified by increasing wave energy conditions, and a supply of fresh sediment from its landward margin. Longshore breakdown and transport of material from the central beach area towards its eastern end has to some extent over-ridden down-beach shape sorting processes. Entrainment forces are such that the shape transition down-beach is more gradual here than at Gileston, while along-beach size sorting takes precedence.

Chapter 7

PEBBLE BEACH HYDROLOGY

"It is not possible for the mind to comprehend, except by a slow process, any effect by a cause repeated so often, that the multiplier itself conveys an idea not more definite than the savage implies when he points to the hairs on his head. As often as I have seen beds of mud, sand and shingle accumulated to the thickness of many thousand feet,I have felt inclined to exclaim that causes, such as the present rivers and present beaches, could never have ground down and produced such masses."

Charles Darwin, 18th March 1835, The Journal of the Voyage of the Beagle.

7.1 INTRODUCTION

All the results presented in Chapters 4, 5 and 6 had one thing in common: the immense variability in forms of beach response to sea waves. Thus, while (1) significant correlations were obtained between certain particle parameters and the speed and direction of dispersion of tracers, a large amount of variation in the data remained unexplained; (2) although beach morphology could be mathematically described and classified, lateral variation under the same apparent littoral conditions impeded accurate modelling; and (3) inspite of success in the identification of differing sediment types, along-beach and down-beach variations often defied facies response predictions. Attempts to include generalised descriptions of process conditions, from wind/wave/tide data, in an explanation of observed beach changes, only underlined the variable spatial and temporal expression of resultant dynamic forces on the shore.

As the investigative work proceeded, this aspect of the natural beach system became increasingly apparent, and it was towards the elucidation of field-based processes that further work was ultimately geared. Following the work of Schiffman (1965), Kirk (1970, 1971, 1973) developed an instrument system for shore process studies and applied it to quantitative measurement of swash zone hydraulics. This investigation produced many new insights into natural beach processes, as well as highlighting the difficulties of developing accurate instrumentation for use in this most rugged of environments. Kemp (1981, pers. comm.) indicated that little further work had been accomplished in this area since Kirk (1975), and it was therefore decided to make a start at up-dating swash zone instrumentation capable of measuring hydraulic phenomenae at high resolution.

The following chapter outlines the successful development of this equipment and gives preliminary results. Because of the limited amount of time that has yet been spent on this work, and the inevitable problems associated with developing and testing prototypes, this discourse represents only an introduction to a new and complex subject. Results are presented, not only because of their contemporary scientific value, but as a means of pointing the way forward to a new understanding of swash and backwash processes. Although the final results chapter in this thesis, it is hopefully also a first in a new phase of work, preparation for which has already been accomplished.

7.2 PREVIOUS WORK

The vast majority of work done since the Second World War on elaborating the properties of sea waves has concentrated on their manifestation seawards of the breaker zone (Fig: 1.2). Some of the conclusions reached have already been discussed in section 5.6. The reason for this bias has been adequately described by Van Dorn (1966, p21) who said:

> "....there is no continuous, self-consistent mathematical description of the behaviour of a periodic wave system of finite height, originating

in deep water, propagating normal to the shore over an arbitrary profile and terminating in uprush and/or reflection from the shoreline. Instead there exists a large number of piece-wise solutions, each of which treats a certain class of waves over a limited range of transformations, until the asymptotic domain of its boundary conditions is exceeded, at which point one must jump to another solution until the shore is finally reached...."

This piece-wise approach has centred on description of deep water and shoaling waves because they are the most amenable to theoretical analysis. This work has been thoroughly reviewed elsewhere (King, 1972; Komar, 1976). However, it is precisely because of the wave transformations which take place within and seawards of the breaker zone that swash/backwash/beach interactions are so complex. Dolan and Ferm (1966, p210) have gone so far as to argue that, "....waves per se have little direct effect on the subaerial beach...." By this they implied that swash and backwash represented physical processes qualitatively different from the periodic surface waves from which they were derived.

Kirk (1970) made the point that, despite a large number of laboratory based studies into wave breaking and swash run-up (Iverson, 1952; Hayami, 1958; Galvin, 1968, 1972; Battjes, 1971; and Meyer and Taylor, 1972), and other theoretical work (Stoker, 1948; Munk, 1949; Biesel, 1952; Carrier and Greenspan, 1958; Shen and Meyer, 1962; Gaughan and Komar, 1975), there have been very few field studies of flow properties shoreward of the breaker zone against which these investigations can be checked. Study of forces active across the foreshore is difficult because of the hydraulic complexity of the environment. Koontz and Inman (1967) have demonstrated that even as shoaling waves approach the breakpoint, an increasing proportion of total flow energy becomes associated with harmonic components of the basic wave motion; a result confirmed inside the swash zone by Huntley and Bowen (1975), among others. This complicates theoretical description of resultant water motion since first order equations no longer apply and higher orders are difficult to work with.

7.3 PHYSICAL PROPERTIES OF THE SWASH ZONE

While the movement of swash is conditioned by breaking wave characteristics, backwash is the result of gravitational forces. Swash velocity therefore depends on wave height and breaker type, whereas backwash velocity is a function of slope angle and rate of groundwater emission from the beach face. Both types of water motion consist of a translatory mass movement which can be described according to the theory of gravity waves. These are horizontal displacements occurring in a single direction, with particle velocities ranging from zero at the bed to a maximum at the surface. The wave forms an isolated crest or bore which has no corresponding trough.

7.3.1 **Wave Asymmetry**

Wave shoaling causes wave velocity and length to decrease until the wave train consists of peaked crests separated by relatively flat troughs. The increasing asymmetry of wave forms and orbital velocities of water particles can be described by successively higher approximations of sinusoidal deep water wave theory (Munk, 1949). Individual particles no longer follow closed orbits and a mass movement toward the shore is initiated. The fact that forward motion of water beneath the wave crest is more rapid than seaward motion under the trough was early recognised as a potential mechanism of sediment sorting (Conaglia's Null Point Hypothesis - in Svendson, 1950). Resultant swash asymmetry has been used to explain the destructive nature of steep waves (Bagnold, 1940; King, 1972).

7.3.2 **Wave Phase Relations**

Palmer (1834, p571) first noted the importance of wave phase conditions on shingle beaches, to which he ascribed the processes of erosion and accretion; "....the difference between the two actions was determined by the rapidity in succession of the waves upon the shore." Kemp (1958, 1960, 1963) in detailed studies of surf and run-up in models and on natural beaches, formalised this aspect in the concept of "phase difference"; the relationship between breaker period (T_b) and swash period (t), being (T_b/t). He demonstrated that the relationship between the phase of a wave at its breakpoint and at the swash limit was indicative of the stability or instability of the profile.

Swash period (t) is described as the time taken between the breaking of a wave and the completion of its run-up on the beach face. When phase difference (T_b/t) is <0.5 each wave is able to complete its run-up and return as backwash before the next wave breaks, so that these rhythmic motions are able to operate independantly of one another. When swash period approaches wave period, backwash cannot clear the foreshore before the next wave arrives. According to Kemp (1960) this enhances erosion of the beach. Three phase levels were identified: waves of low phase were called 'surge' and enhanced deposition on the foreshore; waves of high phase were termed 'surf' and were associated with erosion; waves of an intermediate nature were termed 'transition' and were responsible for the development of discrete areas of both erosion and deposition. Kirk (1975) has taken issue with this terminology because of possible aubiguity with breaker types. He proposed 'low' phase difference for $T_b/t < 0.6$, 'medium' for $0.6 \leqslant T_b/t \leqslant 1.0$, and 'high' for T /t > 1.0.

Phase difference is controlled by swash length, which in turn is contolled by breaker height (Kemp, 1960, 1963). Kirk (1975) concluded that, since natural wave trains are irregular and surf/swash interactions involve a number of phenomenae including wave 'set up' and 'set down', rip currents etc., as well as the simple incoming and outgoing of unit water masses, sea waves actually pass in and out of 'phase' over some characteristic time cycle applying to the conditions. Waves and backwash would be 'in phase' when the outgoing water was cleared before the next breaker occurred. Conversely, as collision between onshore and offshore moving masses would be an 'out of phase' flow condition.

Emery and Gale (1951) suggested that the swash zone (Fig: 1.2) acts as a filter which, because of interference between waves, permits the passage of only larger or longer waves. This, and other studies, have confirmed the central importance of phase relations in swash zone flow structure. Initiation, location and intensity of bed scour, the level of bed sediment entrainment, transport and deposition by swash and backwash, and even the type of sorting pattern imprinted on bed sediment, have all been put down by Kirk (1970) to phase relations. It was his firm contention (Kirk, 1970, p323) that, "Almost all the flow events described and their morphological responses have been demonstrated to be phase dependent".

7.3.3 Turbulence

Wave breaking gives rise to intense turbulence and dissipation of energy, which in turn is responsible for sediment entrainment on the beach. Fluid flow can be of two types; namely, laminar or turbulent. Grant (1948) suggested that a film of water 1cm deep on a sandy foreshore cannot flow faster than 3cm/sec without turbulent flow occurring. Hence laminar flow seldom pertains to the swash zone. Another characteristic of the state of flow which is highly relevant to swash zone hydraulics, is described by the ratio of flow velocity to the velocity of propagation of gravity waves. This ratio is known as the Froude Number (F). When $F<1$ the flow is said to be tranquil (or streaming), and when $F>1$, as shooting (or rapid). Figure 7.1 shows how turbulent, laminar, tranquil and shooting flow combine together.

7.3.4 Particle Entrainment

A stream of water must attain a certain minimum velocity before particles on the bed may be moved. Depending on the speed of fluid flow the sediment motion may be of three types; (1) at low speeds the particles will roll or creep along the bed; (2) at high speeds they will be transported in suspension; (3) at intermediate speeds particles may jump or saltate in response to eddies or abrupt changes of velocity in the fluid. According to Zenkovich (1967) fluid speeds five times that necessary to initiate rolling may be required to achieve suspension. In addition, the speed required to initiate motion (threshold velocity), is always greater than that required to maintain motion of the grain.

The effect of beach gradient is of vital importance in governing particle entrainment. Naturally a particle requires a greater speed of fluid flow to cause grain motion upslope, and a lesser speed for motion downslope. Figure 7.2 expresses this difference in terms of force. The force P1 necessary to dislodge a submerged pebble up-beach of gradient β and limiting angle of repose ϕ is given by:

$$P1 = mg\left(\rho_s/\rho_w - 1\right)\sin\left(\phi + \beta\right)$$

where ρ_s and ρ_w are the specific weights of the pebble and water, respectively. The force P2 necessary to disslodge a pebble down the beach is given by:

$$P2 = mg\left(\rho_s/\rho_w - 1\right)\sin\left(\phi - \beta\right)$$

For gentle slopes the ratio of these pressures is near unity, but for steeper slopes the difference is appreciable and implies considerable asymmetry of flow.

The movement of coarse material occurs dominantly as bed-load, although saltation and suspension can be instigated under high phase conditions. Near the swash limit, where flow is shooting, saltation of particles can frequently be observed. A good deal of theoretical work has been carried out on the description and prediction of littoral sediment transport. Bagnold (1968, p48) suggested that collisions between large numbers of particles "....result in a dispersive stress....which supports the bed-load against gravity as a dispersed cloud, and maintains the dispersion in a state of statistical equilibrium".

7.3.5 **Swash Velocity**

Dolan and Ferm (1966) proposed that one parameter reflecting the application of swash energy across a beach, was the velocity of the leading edge of the swash. Dolan and Ferm (1966) successfully correlated swash velocity with beach slope, and found a correlation between swash velocity and deep water wave height. It was noted, however, that these correlations became weaker as energy conditions (wave height) increased. This represented the influence of phase relations, since wave height controls swash length which in turn controls swash period.

In his study of swash processes, Kemp (1958) derived expressions for swash velocity and for swash length. Swash length was given by:

$$l = (0.5\ K\ g\ H_b)^{0.5}$$

where l is swash length, K a coefficient, g the acceleration due to gravity, and H_b the breaker height. Swash velocity, Cx, was given by:

$$Cx = [K\ g\ H_b\ (1 - X l^{-1})]^{0.5}$$

where X is the distance landward from the breaker zone to the point being considered. Kemp (1958) also identified a 'critical' swash length based on the phase difference t = T, such that for a given wave period, T, the critical length of swash was given by:

$$T = 2l\ (K\ g\ H_b)^{-0.5}$$

Kirk (1975) used observed breaker height and swash length data to solve K in the above equations. A value of K = 1.28 was obtained, and Kirk (1970) used this to plot the relationships shown in Figures 7.3 A-B. It can be seen from Figure 7.3A that there is a rapid increase in 'equilibrium' swash length with breaker height, and that this is theoretically especially pronounced for longer period waves. Figure 7.3B indicates the velocities which should theoretically obtain at given distances throughout the swash zone for breakers of varying height. It is noticable that near-linear decreases in velocity are predicted for most of the swash, with rapid declines near the landward limit of flow. The main disadvantage of studying velocity profiles of swash fronts is that they are atypical of the flow body behind them (Kirk, 1970).

7.3.6 Beach Watertable and Tidal Influences

Grant (1948, p655) found that the position of beach sub-surface watertable was an important factor in determining erosion and deposition, "....high watertable accelerates beach erosion, and conversely, low watertable may result in pronounced aggradation of the foreshore." Since this time the full significance of beach watertable and its relationship to the tidal cycle, have been elaborated by many workers (Emery and Foster, 1948; Watts and Deardruff, 1954; Duncan, 1964; Otvos, 1965; Strahler, 1964; Wadell, 1973; Williams, 1975). Results have shown that changes in the watertable take place continuously throughout the tidal cycle. A 'dry' foreshore with a low watertable is conducive to swash deposition, whereas a 'saturated' foreshore with a high watertable creates a strong outflow of percolated water resulting in backwash erosion. Because of a lag in the adjustment of watertable level to tidal fluctuation in still water level, these conditions alternate throughout the tide (Strahler, 1964).

Wadell (1973) monitored ground water level in a well dug five metres inland of a sandy foreshore. He discovered that the pressure head of swash arriving at the shoreline induced an instantaneous response, followed by a lagged rise in water level. This lag resulted from the frictional retardation of horizontal mass flux travelling through the saturated beach layer. The beach matrix and beach slope both acted as a low-pass filter, whose cut-off frequency underwent red shift with distance landward from the shoreline. One of the key factors controlling this effect was beach permeability. Landon (1932) highlighted the importance of this aspect by suggesting that permeability in the vertical direction and surface run-off were inversely related. Figure 7.4 indicates the likely water budget of the swash zone which, as Kirk (1970) has pointed out, is also under the influence of wave phase relations.

7.4 MEASURING FLOW PRESSURE IN THE SWASH ZONE

Certain practical considerations had to be made in designing instruments for use in the swash zone. Swash and backwash processes are translational movements of bodies of water, which, because of percolation into the beach face are usually of small depth. The turbulent nature of flows means that the presence of moving particles in the water column effectively precludes the use of conventional devices for measuring fluid flow, such as pitot tubes and propeller driven current meters (Schiffman, 1965). Even electromagnetic current meters would need considerable modification to be of any use. One potential method is to track 'parcels' of water with tracers or floats (Miller and Zeigler, 1958), but such objects may behave in an anomalous fashion because of inertial effects. It is to some extent easier to measure flow properties at some fixed point, which, because of tidal translation, will occupy a variety of relative positions in the swash zone. It is also clear that changes occur rapidly in this zone, and process/response phenomenae therefore operate at a range of differing timescales.

7.4.1 **Kirk's (1973) Instrument System**

The main item in Kirk's (1973) system was called a dynamometer, and was purported to be able to measure both swash and backwash flow velocities. This was based, with little alteration, on the instrument used by Shiffman (1965). It measured the net force exerted on two discs, by determining the resultant displacement of a central rod coupled to a shore based analogue chart recorder via a waterproof cable. Moving parts of the dynamometer were housed in a watertight, oil-filled brass container which was anchored to the bed by a framework driven into the beach.

The overall geometry of the device and particularly the presence of the spring housing (Fig: 7.5) was considered to represent a major shortcoming. The device did not possess either a pebble-like configuration, or a simple form such as a sphere or cylinder. This problem was acknowledged by Kirk (1970) who proceeded to calibrate the instrument under steady flows of up to 1.1 m/sec (calibration in a wave tank rather than a flume would have been more desirable, however none was available). The resulting calibrations were not linear as both discs (Fig: 7.5) had an initial region of slow response which was caused by mechanical friction in the instrument. Caldwell et al., (1982) were of the opinion that considerable errors could be encountered by using static and steady flow calibrations to determine fluid velocity in the turbulent swash zone, even with a regularly shaped sensor on which some theoretical analysis could be undertaken. As a result, both Kirk's instrument and those yet to be described, are considered to be force transducers (or load cells) rather than dynamometers.

Other shortcomings in the design which were identified were:

1. The overall strength of the device which rendered it unsuitable for applications where its discs could come into collision with fast-moving particles of appreciable mass (0.5Kg moving at 1m/sec). Although Kirk (1970) used his instrument in a high energy environment, it was clear that both Gileston and Nash beaches represented much more abrasive systems because of the size of material, which was a factor of 10 times

larger than that encountered by Kirk.

2. The mechanical friction that existed at the rod seals which caused loss of resolution at low flow pressures. In terms of Sutton's (1955) classification of turbulence scale, the instrument was not sufficiently sensitive to justify detailed assessment of eddies having velocity fluctuations of less than a second.

3. The considerable length of the sensor (approximately 0.5m) which limited measurements to eddies with lengths greater than one metre.

7.4.2 The New Instrument (Mark I)

Most of these difficulties were overcome in a new design, the details of which are schematically illustrated in Figure 7.6 (Caldwell et al., 1982). In outward appearance the instrument is simply an aluminium cylinder supported on a steel rod which can be fixed to an anchoring point (Plates 18-19). As a wave exerts a force on the outer casing, the outside cylinder, ends, central rod and electrodes move against the stiffness of the stainless steel diaphragm springs, relative to the stationary inner cylinder. The amount of displacement, which represents the applied force, is measured electronically from the resulting change in capacitance (C1) between electrodes A and B, and capacitance

(C2) between electrodes C and D (Fig: 7.6). As a safeguard against damage to the electrodes resulting from axial collisions by large particles, gaps E and F were adjusted so that maximum movement in either direction was only 0.5mm. The average gap between the electrodes was 1mm. Since the support rod, and hence the inner cylinder, were firmly anchored to a solid base, the only effect of the rod was to marginally redirect flow around the outer casing.

Capacitors C1 and C2 (Fig: 7.7) were arranged with C' C" and C' << C1 or C2. Analysis of the circuit yields the result:

$$V_o' = V_s \,(k\,\Delta x + k')$$

where Δx is the displacement of the outer cylinder, and k and k' are constants, with k' << kΔx for most values of Δx. V_o' and V_s represent phasor quantities, therefore the direction of Δx is given by the phase relationship between them. The second differential amplifier (Fig: 7.7) subtracts V_s from V_o' resulting in an output where:

$$|V_o| = k''\,(\Delta x + k''')\,|V_s|$$

in which k" and k''' are constants. The output is rectified and displayed on a pen recorder.

The thickness of the cylinder's curved surface, ends and diaphragms were based on the following considerations:

1. The total mass of all moving sections should be the same as the mass of water displaced to prevent zero shift due to gravitational forces when the transducer is fixed in a non-horizontal position and completely immersed.

2. Diaphragm thickness and total mass of moving sections should be such that the time constant of the system is short and allows an easily measured displacement.

3. The whole of the cylinder and especially the ends, should be as strong as possible.

These requirements were met with the design used, the time constant of the transducer in water being approximately 90 miliseconds. When in use an electrical signal (V_o') from the transducer was transmitted to an on-shore control unit by a multicore cable placed inside a length of strong PVC pipe for protection. The output was then displayed on a chart recorder (Plate 20). Since the instrument was considered to be basically a device for measuring force on pebble-like objects, it was only calibrated with static loadings. This was considered satisfactory since the time constant was much shorter than the times of any events which the transducer was required to detect and resolve.

7.4.3 The Wave Height Recorder

Following Kirk's (1970) approach, an attempt was made to concurrently measure not only swash and backwash flow pressures, but also the height of the water column as these pressures operated. A wave height recorder was designed along lines proposed by Wadell (1973), using a metal lead encased in a synthetic jacket. When placed in salt water the lead acted as one plate of a capacitor, and the water as the other. The dielectric was provided by the jacket. The resulting capacitance (C) was linearly proportional to the immersed length of the lead.

Because of the inhospitable nature of the environment in which it was used, the metal lead had to be placed inside a length of scaffolding pipe peppered with enough holes to allow sea water to enter or escape at speed. This was welded with supporting struts onto the same steel top plate to which the swash force transducer was clamped (Plates: 18, 19 and 21). The lead was held under tension between a small nylon housing (containing an amplifier) fixed into the base of the pipe, and an aluminium clamp at its top. To prevent the lead coming into contact with the sides of the tube, three nylon spacers were placed inside the tube at various points. The instrument was cheaply made, and relatively easy to calibrate in a tank, but in practice did not work very satisfactorily for reasons given later.

7.4.4 **Swash Force Transducer** (Mark II)

Although the majority of the results presented here were obtained using the Mark I version of the swash force transducer (section 7.4.2), a later version was developed along different principles. Although these were not as theoretically exact they did incorporate a simplicity that was found essential in field equipment. Figure 7.8 shows the schematic construction of this second prototype. It was based on the measurement of variable resistance across strain guages as they distorted in response to stresses applied to a solid steel support rod via a sensing head. Figure 7.9 shows how the strain guages were arranged in standard bridge formation. There were several advantages to this design:

1. Unlike the Mark I version which required an oscillating square wave AC supply, the Mark II version was powered by a 5 volt DC supply which was both simpler to produce, and could be connected directly to the chart recorder.

2. No electronic equipment was located in the sensing head, which could then easily be removed and replaced.

This enabled the production of sensing heads in the shape of natural beach material.

3. There were infact four strain guages fixed to the support rod (as displayed in the lower half of Figure 7.10) so that longshore flow pressures could be recorded, as well as those of the swash and backwash.

4. The number of water-tight seals was reduced to a minimum.

The support rod was placed inside a steel tube, which was subsequently filled with an inert viscous damping fluid to reduce short period vibrations caused by axial collisions with beach material (Fig: 7.8). The aluminium sensing head (only one has been produced to date) was partially hollowed out so that its immersed mass equalled that of the water displaced. An 'O' ring stop was incorporated to prevent the support rod from coming into contact with the surrounding steel tube. A small amplification unit was placed inside a cylindrical brass housing, from which a cable passed directly to shore. This brass housing was filled with silicone jelly to ensure sea water did not damage the electronics.

The instrument was anchored to the beach as shown in Plate 22. Some slight inaccuracy resulted from the fact that a similar force applied at different points on the sensing head (i.e. at A and B in Fig:7.8) would produce marginally different stresses on the support rod; this being of greater significance when using a spherical sensing head. This problem was not considered prohibitive, and the transducer proved a robust and effective piece of equipment.

7.4.5 **Swash Velocity Marker Poles**

Because the transducers were only thought capable of measuring flow pressures, a method was devised along the lines adopted by Dolan and Ferm (1966) for recording swash velocities. It was obviously impossible to drive stakes into the beach surface, as Dolan and Ferm (1966) were able to do on the Outer Banks of North Carolina. It was also necessary to use particularly long stakes ($\simeq$4 m), since tidal translation over the steep gradient beach face would soon cover anything smaller. Consequently, six heavy duty marker poles were constructed, and these are shown being prepared for use on the beach in Plates 23 and 24. Three 30Kg concrete anchoring legs were first buried in the beach face (Plate 25). These were bolted to a steel collar through which a 30mm diameter pole was passed (Plate 26). This was also bolted in place and jubilee clips fixed either side of the collar to prevent it being lost if (or rather, when) the pole eventually collapsed under heavy seas.

If time permitted, all six marker poles were assembled on the beach prior to the tide reaching the ridge base. It was impossible to fix them an equal distance apart, although this was approximated. Therefore the exact distances between the poles, and their location on the profile was recorded before monitoring began. A Rustrak Event Recorder (Plate 4) with a manual trip-pen device was used to record the time taken by a series of swash edges to pass between each marker rod. A sample of 20 consecutive swashes was monitored at various stages of the tide. It was not possible to record backwash velocities using this method. The event recorder was also used to obtain breaking wave period, swash period and run-up period.

7.5 PRACTICAL APPLICATION OF SWASH ZONE INSTRUMENTATION

Because much of the available time was utilised in field-testing and improving the equipment's performance, it is worth making some comments about its practical application and problems associated with measuring hydraulic properties in the swash zone. The first decision which had a profound effect on the results of this work was to select Nash beach as the sampling location. This was done because it was only possible to monitor swash processes when high tide occurred at mid-day; a two hour preparation period was necessary before a flowing tide reached the ridge base (this usually took place around two hours before high tide). A further two hour dismantling period was required during daylight hours after the tide had receeded from the beach ridge. Unfortunately, in the Bristol Channel such high tides (1100-1500 hrs) coincided with neaps, and in these circumstances reasonable sized waves and coverage of the beach face could only be guaranteed at Nash.

Plates 27-30 provide examples of the sizes of material regularly found on the beach surface near Nash Point. The swash transducer was anchored at the C2 sampling point on cross-section 4 at Nash (Figs: 5.7 and 6.14). Swash velocity marker poles were positioned slightly to one side of this cross-section. Although the conditions encountered justified the choice of Nash beach, this location represented one of the most rugged and inhospitable of all coastal environments. Equipment had to be equally rugged and robust, to keep out sea water and survive the intense abrasive forces generated by saltating cobbles.

The first difficulty was to establish some form of anchorage for the transducer and depth guage. It was impossible to follow Kirk's (1970) procedure of pushing a steel support frame into the beach surface, since this would soon have been mangled wreckage. A trench had to be dug into which a large rectangular boulder (>1 tonne) was rolled. A specially designed 0.5" steel base plate was pinned to its top surface with six 8mm rawl bolts. When the trench was filled in the base plate was covered to a depth of around 0.5m. It showed no sign of movement throughout the remainder of the research.

The plate was located by use of a metal detector. Once uncovered, three tubular support legs were used to bolt the top plate (onto which the instruments were clamped) to the base plate with stainless steel bolts (Plates 18 and 19). Three sizes of leg were available (3", 6" and 9"); that being used chosen so as to ensure the sensing head was as close as possible to the beach surface. On several occasions the beach profile was such that the base plate was exposed. When this happened it was impossible to fix the sensing head nearer than 0.5m from the surface (Plate 31).

The major difficulty encountered during this work concerned the transmission of input and output signals between the shore unit and instruments. The original transducer and depth guage were connected by external cables which were attached to the transmission line via an aluminium underwater connector plug (Plates 18-19). This latter component was designed for use at depth, rather than on a wave pounded beach surface. It regularly failed within the first hour of monitoring.

The transmission cable also proved unsatisfactory. It was constructed from a 40m length of domestic mains water supply pipe, along which two multicore electronic leads were threaded. It formed a tough protective casing which lasted a considerable time, but it was susceptible to lateral swash and backwash currents which twisted and flexed it until the connector plug attachment gave way. A nylon rope and steel hawser anchor line fixed to cliff based pitons were necessary to hold it steady during monitoring (Plate 32).

The strength and effectiveness of the equipment was tested many times. On one occasion (27.11.80) it was deployed in storm wave conditions. Plate 33 shows the instruments under a four metre breaking wave. Intense amounts of energy were released during the occurrence of these massive hydraulic jump waves, but unfortunately on this occasion the transmission line was unable to withstand the conditions and little useful data was gathered. However, although the depth guage suffered a 20° bend, the transducer was found to be still functioning on its return to the laboratory (Plate 34). The depth guage did not prove very satisfactory because tension on the capacitance lead was heightened by swash flow pressures which stretched and slackened it until it touched the sides of the protective steel tube. Thus it also only worked for a limited period during monitoring.

Finally, there was the problem of transporting and assembling well over 1000Kg of equipment, most of which had to be carried 300m around Nash Point from the nearest access

(Fig: 5.7). A strict and disciplined working procedure had to be adopted to ensure everything was properly constructed, and all appropriate beach measurements taken. The speed of the incoming tide kept motivation and concentration levels high. There were many disappointments during this work, but it was stimulating and instructive, and the limited results promised much for the future if efforts are maintained.

7.6 RESULTS

7.6.1 Introduction

Eighteen separate experiments were carried out on Nash beach to investigate swash zone hydraulic processes, of which fifteen yeilded some useful results (Table: 7.1). In November 1979 a series of swash velocity experiments were initiated (section 7.4.5). Then, during 1980, the first prototype swash transducer (section 7.4.2, Fig: 7.6) was designed and constructed. Field testing of this instrument commenced in November 1980, and included the damaging event of 27.11.80. The first meaningful results were obtained on the 27th of February, 1981. Thereafter, a further five experiments were undertaken. The last two experiments of this sequence were carried out using the Mark II version of the swash transducer (section 7.4.4). Measurement of swash velocity was included in four out of the six swash transducer experiments.

7.6.2 **Swash Velocity**

Results were obtained for 13 experiments (Table: 7.1). Figures 7.11A-T show examples of the format in which the results of each sample were output by the computer. The lower third of each diagram shows the profile configuration before (solid line) and after (broken line) the experiment. Vertical lines indicate the position of beach marker rods. The middle third shows the velocity data (in metres per second) in terms of a vertical bar. The centre of the bar indicates the mean swash velocity of the sample, and its respective ends represent one standard deviation either side of the mean. Where two or more velocity results are indicated, each mean position is joined by a line to give an impression of whether mean velocity increased or decreased between marker rods. The top third shows vertical blocks indicating the sample number (i.e. $\leqslant 20$).

Figures 7.12A-M provide the actual mean velocity values for each experiment (sample numbers are inset and ringed). Vertical divisions on the righthand sides of these figures indicate rod positions in relation to the ridge base. As various marker rods collapsed during each experiment, their loss is indicated by their ommission from the figures between one sample and the next. As well as surveying the profile configuration, surface sediment was also sampled before and after each experiment. This was done using a modified standard sampling routine (section 3.3.1). Figures 7.13A-O show how these results were output by the computer.

The lower third of each diagram shows the profile configuration before (solid) and after (broken), as well as the various sediment sampling points. Every effort was made to sample from the same area before (solid vertical line) and after (dotted vertical line) each experiment, so that samples could be usefully compared. The middle third shows the position of each sample's mean shape (asterisk - before, cross - after) on triangular Folk diagrams (section 3.2.2, Fig: 3.2). The top third shows the mean particle size (C-axis) of each sample. The centre of each horizontal bar represents the mean value, and the bar ends indicate one standard deviation on either side. The lower bar represents the pre-experiment sample, and the higher bar represents the post-experiment sample. A Chi-square (non-parametric) statistical test was carried out on each pair of samples to identify significant differences between size data. The results are also indicated on Figures 7.13A-O. This test was based on the same principles as that for tracer/host tests (section 4.4.2). The data on which Figures 7.13A-O are based, plus the coordinates of pre and post experiment profiles, are given in Appendix 7.1.

7.6.2.1 General Swash Velocity Patterns

An attempt was made to discern general velocity patterns across (down) the beach ridge profile during the 13 experiments. Using the ridge base as a reference point, mean velocity values obtained between each pair of marker rods were averaged. This average value was then plotted in Figure 7.14, using the distance between the ridge base and the mid-point between marker rods as a means of locating it on the horizontal axis. Thus, for the two mean velocity values recorded between rods 1 and 2 on 1.11.79 (i.e. 2.89 and 4.55 m/sec - Fig: 7.12A), 2.89 was multiplied by the sample number of 11, and 4.55 by the sample number of 20, the results added together and divided by 31 to obtain 3.96 m/sec. This value was then plotted on Figure 7.14 at a distance of 3.5 from the ridge base. This implied that for results obtained on 1.11.79, average swash velocity around a point 3.5m from the ridge base was 3.96 m/sec. Using all the data available from Figures 7.12A-M in the same way it was possible to construct Figure 7.14.

Although it was thought that there might be specific points of peak velocity on the beach profile, none was to be found in Figure 7.14. Instead, a range of velocity values was recorded throughout the length of the profile. The scatter of points increased up-beach reflecting a fall in sample size and a greater variability in velocity values associated with the swash tip. It was also clear that recorded swash velocities on Nash beach were of an order of magnitude higher than encountered by both Schiffman (1965) and Kirk (1970). The former quoted two modal values of 1.3 m/sec and 1.9 m/sec, while Kirk (1970) produced results up to a maximum of 2m/sec. The average swash velocity for Nash beach lies above 4 m/sec according to the results in Figure 7.14. The reason for this disparity is not clear, although factors such as the steep beach slope gradient and general wave regime at Nash must be partially responsible. Schiffman (1965) worked on two Californian sand beaches, and Kirk (1970) located his experiments on some mixed sand and gravel beaches on the east coast of New Zealand.

It was felt that the significant translation in tide level, which occurred during each experiment, could have obscured any sought-after variation in swash velocity across the profile. Therefore the data contained in Figures 7.12A-M was replotted in Figures 7.15A-E. This time, individual velocity scores were plotted according to whether they were recorded in one of five distinct phases before high tide. Thus, for the two mean velocity values recorded between rods 1 and 2 on 1.11.79 (i.e. 2.89 and 4.55 m/sec - Fig: 7.12A), 2.89 m/sec at 3.5m from the ridge base was plotted on Figure 7.15B because it was recorded between 2 and 1.5 hours before high tide, and 4.55 m/sec at 3.5m was plotted on Figure 7.15C because it was recorded between 1.5 and 1 hour before high tide. Unfortunately, this method ignored sample number, and therefore the representative nature of each velocity value.

Figures 7.15A-E show distributions of velocity values encountered as the tide rose across the ridge to high tide level during each experiment. The scatter of points on each diagram was such that no significant peaks or troughs could be seen. Localised peaks and troughs were apparent, but these were associated with particular experiments during which higher or lower than average swash velocities were encountered. It was therefore impossible to generalise that velocities increased or decreased as each swash moved up-beach, or that there was a velocity peak or trough between the ridge base and swash limit. Neither was it possible to identify different distributions of velocity throughout the flooding tide.

Figures 7.14 and 7.15A-E were generally similar to the swash velocity distribution according to Kirk (1970), which is shown in Figure 7.16. This diagram shows that swash velocities remained relatively unchanged throughout the majority of their passage over the beach face, terminating abruptly at the swash limit. Because of potential complications caused by variations in wave parameters (notably wave breaker type) between each experiment, which could have produced specific velocity distributions, some of the individual experiments were examined in detail.

7.6.2.2 Wave Parameter Correlations

Table 7.1 shows the variation in wave parameters recorded during the 15 swash zone experiments. Swash velocity is given as the average recorded between marker rods 1 and 2 during each experiment. Breaking wave height (H_b) was recorded visually in feet and converted to centimetres. Breaking wave period (T_b) was calculated after using the trip-pen event recorder (section 7.4.5) to sample over 50 consecutive waves. The deep water wave equivalents of these two values (H_o and T_o) were obtained from HRS Severn Estuary Wave Climate Study data taken from buoy B (Figs: 2.9A-F). There was an immediately noticable disparity between T_b and T_o, such that the former could be over three times larger than the latter. The reason for this was unclear, although 'red-shift' caused by interference in the shoaling zone could have been partially responsible. In addition, it is likely that the rider buoy would have been sensitive to the smaller waves in any wave pattern, generally disregarded in a visual assessment; although the use of $\bar{H}_3$ by HRS should have compensated for this.

The swash period, shown as t in Table 7.1, was also obtained using the event recorder. It was used to calculate Kemp's (1960) 'phase-difference' (section 7.3.2), shown as t/T_b.

Because of an error in the measurement of swash period prior to 1981, phase-difference could not be calculated for experiments before this time. Finally, run-up period, r, which represents the mean period between the arrival of a sample of consecutive swash tips, was also calculated using the event recorder during each experiment. This value was useful because it could be used in conjunction with T_b to ascertain the level of swash interference occurring on any date. If the incoming wave field was regular, then minimum interference between consecutive translatory swashes would be expected in the swash zone. T_b and r on this occasion would be roughly equivalent. If the incoming wave field was highly irregular (perhaps consisting of more than one set of waves), then swash/swash (as opposed to swash/backwash) interference would be expected. The resulting 'red-shift' would tend to increase run-up period, r, with respect to T_b.

Data in Table 7.1 was used to identify correlations between wave parameters. The results of some correlation tests are shown in Table 7.2. Highest correlation coefficients were obtained from comparisons between H_o and T_b, and T_o and H_b. Why this should have been the case when the coefficients obtained from comparisons between H_o and T_o, and H_b and T_b were considerably lower, is unknown. Generally, correlation coefficients are low in Table 7.2, and the sample number of 10 meant that results were not statistically significant. There was, for instance, no relationship between swash velocity and H_b or H_o, as found by Dolan and Ferm (1966), although the permanence of their beach marker rods, and the use of cine equipment and an off-shore wave rider buoy, enabled these investigators to use a far larger quantity of data, at a greater level of accuracy, in their calculations.

There was, however, a more definite correlation between phase-difference and H_b, as predicted by Kemp (1960). The coefficient of correlation was 0.7 at N = 6, although not statistically significant. This relationship reflected the association between wave height and the quantity of water brought onto the beach surface. Greater quantities of water take relatively longer to drain from the beach surface as backwash, and enhance the likelihood of interference between swash and backwash. Thus, for a given wave period, an increase in wave height induces an increase in phase-difference. Apart from this result, correlations between wave parameters were extremely poor and must have resulted from (1) the relative inaccuracy with which some parameters were obtained (despite effort), (2) the need to use mean values, rather than individual measurements relating to separate waves, and (3) the only indirect relationship between offshore wave parameters and nearshore wave processes.

7.6.2.3 Some Specific Experiments

1st November 1979

The first swash velocity experiment was carried out on this date. Conditions were medium/high energy for Nash beach with H_b averaging 106cm (3.5'), and T_b averaging 8 sec. Seven marker rods were assembled, and on this occasion two depth of disturbance experiments were also prepared by painting a plug of material to a depth of 50cm at points midway between rods 1 and 2, and 4 and 5, respectively. Figures 7.11A-F provide swash velocity results for all six samples. The wave breaker type was plunging. This form was encouraged by the strong southwesterly winds which were blowing.

Sample 1 (Fig: 7.11A) was recorded when waves were breaking out over the shore platform, so that only the swash tips of the largest waves reached the first two rods. Sample 2 (Fig: 7.11B) was recorded when waves were breaking at, or near the ridge base. Results showed a general decline in velocities between rods 1 and 3, although a few of the largest waves reached rod 4 and produced slightly increased speeds at that point. Reference to Figure 7.12A gives the velocity values for this sample as 4.55, 3.59 and 4.03 m/sec respectively. By sample 3, waves were breaking around the position of rod 1 (this having already collapsed). High velocities of around 4.7 m/sec prevailed between rods 2 and 4, although there was now a decrease in speed of those swashes which reached rod 5 (Fig: 7.11C). During sample 4 waves were breaking around rod 2. Rod 3 had collapsed, and the most notable feature was that velocities had become more even, producing lower standard deviations (Fig: 7.11D). Those waves which reached rod 5 produced slightly high velocities. Samples 5 and 6 (Figs: 7.11E-F) produced little additional information since the majority of rods had collapsed by this time.

Figure 7.13A shows that the effect of these relatively high, plunging waves was apparently 'constructive', although whether the upper beach fill was created from lower beach cut, or the new configuration represented a longshore redistribution of material, was not clear. The only statistically significant differences between sediment samples concerned those collected from the B position. However, the second (post-experiment) sample was inadvertently collected from the upper beach berm base and was not strictly comparable with the first. The most interesting aspect of these results was that velocities associated with the swash tip were highly variable giving a large standard deviation to results. It contrast, velocities recorded at, or immediately landwards of break point produced more regular values. When the sites of both depth of disturbance studies were located, all marked material had been dispersed, confirming that disturbance in excess of 50cm had taken place on the beach surface.

13th November 1979

Despite the fact that a large proportion of equipment had been buried beneath the beach surface on the 1st of November (it had to be recovered using a metal detector), a second experiment took place at the following neap tide. H_b was recorded at 56cm (1.5') and T_b at 8 sec. Wave form was plunging and there was an easterly breeze. Figures 7.11G-M show the velocity results for seven samples taken on this date. Waves only advanced as far as rod 4, but their velocity distributions confirmed the results of the previous experiment. Standard deviations decreased between swash tip and breaking wave point. The majority of samples showed velocities gradually increased towards the swash tip. Figure 7.12B also shows that velocities between rods 1 and 2 gradually increased as the tide rose until a peak speed around 3.9 m/sec was obtained.

Figure 7.13B shows that despite considerable alteration to the lower profile configuration, sediment sample size comparisons did not produce any significant results. However, material at sample point C was found to be considerably more spherical and regular in size after the experiment (Appendix 7.1). A bank of material had been built up at this point, and sub-facies resembled Lower Beach Berm Top (LBBT) sediments (section 6.8.8). The tail of large sediment sizes present at this point had obviously been infilled with mobile spherical material, under 'constructional' conditions. Plunging waves could be clearly observed pushing forward material landwards of wave break. A few of the waves at high tide managed to breach this ridge, forming small channels which might have assisted in the development of cusps in the correct conditions.

<u>27th November 1979</u>

Waves were long period southwesterlies (T_b = 10 sec) which broke in spilling form (H_b = 91cm/3'). Figures 7.11N-T show the velocity results for this experiment, which produced some of the highest speeds. Most samples showed the same increased variability in swash tip speeds observed during earlier experiments. With the early collapse of rod 1, it was necessary to examine velocities recorded between rods 2 and 3 on Figure 7.12C (disregarding the single sample 1 result) to observe a steady increase in wave speeds to a maximum of 5.46 m/sec, 45 minutes before high tide.

Figure 7.13C shows that conditions were 'destructional', considerable cut taking place along the whole profile affected by waves. Samples from points A, B and D recorded statistically significant results from particle size comparisons. Only samples from point C recorded obvious variation in mean particle form, the post-experiment sample being slightly more spherical (Appendix 7.1). Whereas to the point of maximum run-up. From observation, it seems that the distance over which the decrease takes place is usually much smaller than the average distance between marker rods during the experiments ($\simeq$ 5m). This accounts for the increased variability of swash speeds recorded at the swash tip. Some waves may have been in the process of decelerating when they reached the most landward marker rod, whereas others may still have been moving at (almost) their original propagation speed.

7.6.3 **Swash Transducer Pressure Recordings**

7.6.3.1 Introduction

Only six experiments involving either the Mark I or II version of the swash transducer were conducted (Table 7.1). As results were highly variable it is intended to deal with each experiment separately. General conditions are illustrated by a series of plates, and results are shown in the form of sections of the analogue chart record (Figs: 7.17A-C, 7.18A-B, 7.19A-E, 7.20A-D, 7.21A-G and 7.22A-D).

7.6.3.2 27th February 1981

Plates 35 and 36 show the general littoral conditions before and after high tide, respectively. A south-southeasterly wave field (T_b = 10.9 sec, H_b = 46cm/1.5') prevailed, sediment from the upper beach (point A) showed a slig decrease in particle size, that from points B and D show an increase. Given the relationship between particle shape and the C-axis (section 6.7.2, Figs: 6.28A-F), it appeared as if down-combing could have favoured the removal of rods and spheres from the upper beach. However, only a slight and barely detectable shift in mean form (shape), towards a more oblate characteristic, was recorded on the Folk shape triangle for point A sediments (Fig: 7.13C).

7.6.2.4 Discussion

The next five experiments, up to 24.3.80 (Table 7.1), were associated with relatively calm conditions and only minor post-experiment beach alterations. The final five experiments are referred to in connection with the swash transducer results. Information arising from swash velocity experiments has been of limited value in elucidating the distinctive nature of swash zone depositional processes. Velocities appear to be generally high on Nash beach, compared with published results for sand and sand/gravel beaches. Swash speeds are generally more regular in value close to wave break point, becoming highly variable at the swash tip.

Velocity values remain fairly stable throughout the passage of a wave up-beach, until a sharp decrease takes place near producing a phase-difference of 0.36 (Kemp's (1960) surge phase). On this occasion the Mark I transducer was used in combination with the depth guage. Figure 7.17A shows the analogue record at 1000hrs when swash velocity was recorded at 4.31 m/sec around the instruments (Figs: 7.12J and 7.13J). Although the depth guage indicated its entire length was repeatedly covered by waves at this time, a large proportion of the pen deflection was caused by spray contact with the wire electrode. This was a common failing in signals from this piece of equipment. The considerable 'zero shift' in depth guage signals was also due to variable drainage time of sea water from the electrode between waves.

At this time the swash transducer was being affected by flow pressures near to the swash tip. It had been impossible to anchor the sensing head close to the beach surface because of the low elevation of the lower beach, which had exposed the base plate. The sensing head was therefore affected by higher swashes, producing intermittent deflections in the trace. Backwash, which drained beneath the instrument, was missing from the record. Recorded flow forces lay between 1-6Kg/79cm^2 (the diameter of the cylinder ends was 10cm) or 7.6gm/cm^2. These forces prevailed for only a second or so, as the turbulent swash front passed the instrument.

Figure 7.17B shows the analogue record at half speed. Peak pressures were of up to 8Kg/79cm^2 (10.2gm/cm^2). There was some zero-shift in the transducer during this time due to unavoidable internal mechanical adjustments. By 1110hrs (Fig: 7.17C) the depth guage record had become totally unreliable and had been switched off. The transducer was being affected by short duration swash forces up to $17Kg/79cm^2$ ($21.6\ gm/cm^2$), although these values may be excessive because of mechanical inertia in the recording pen which tended to enhance deflection during short duration pulsed signals. These pressures were, however, sufficient to transport all the sediment sizes apparent in Plate 35.

Figure 7.17C also shows evidence of backwash flow pressure. Small amplitude deflections towards the graph base represent the first phase of backwash; large amounts of beach-bound water continuing to flow beneath the sensing head. Figure 7.13J shows that despite the ability of wave forces to move a large size range of material, there was little alteration in profile configuration or sediment sub-facies structure. Swash forces were probably of such short duration that net sediment transport was restricted to only a localised scale.

7.6.3.3 14th March 1981

Plate 37 shows the conditions prevailing on this date. A strong southwesterly swell predominated (H_b = 122cm/4' T_b = 8.2 sec) producing a phase-difference of 1.32 (Kemp's (1960) surf phase). Run-up period r was 8.4 sec indicating a very regular wave field. Figure 7.18A shows the analogue record from depth guage and Mark I transducer at 1110hrs. The deflections indicated at (i) were produced by the swash shown in Plate 38. This illustrates the problem of spray wetting the depth guage electrode. Peak flow pressure was recorded as 7.67Kg/79cm^2 (9.7gm/cm^2). Only a small backwash pressure accompanied this wave partly because the sensing head could only be anchored some 20cm above the beach surface.

At 1130 hrs when swash velocity was averaging 3.8m/sec (Fig: 7.12K), considerable levels of backwash pressure were being recorded (Fig: 7.18B). Waves at this time were breaking around the instrument, although flow pressure values had generally fallen to around 2-4Kg/79cm^2 (2.5-5.1gm/cm^2), and were sustained over a longer period than swash. Minutes after the trace in Figure 7.18B was obtained the transmission line from the instruments to shore sustained damage, and the signals ceased.

Figure 7.13K shows that detectable changes took place to the size composition of material at two of the lower beach sampling sites. Little change could be detected to the profile configuration, which was one of Concave, Lower Berm (CCLB). With phase-difference > 1.0 and surf-phase conditions prevailing, 'destructive' swash zone processes would probably have simply reinforced the storm-type profile configuration. In this situation it was unfortunate that the sensing head was positioned significantly above the beach surface.

7.6.3.4 10th April 1981

Plate 39 indicates that conditions were relatively calm on this date. Largely for this reason it was possible to continue recording swash/backwash flow data throughout the complete flooding/ebbing tidal cycle on the pebble ridge. A low amplitude southwesterly swell was present (H_b = 46cm/1.5', T_b = 5.7 sec). This produced a phase-difference of only 0.56 which lies on the borderline between Kemp's (1960) surge and transition phases. Run-up period was 10.1 sec, which suggested a very irregular wave pattern. Figure 7.19A shows the analogue traces of Mark I swash transducer and depth guage at 1015 hrs (note that the pressure trace is now the lower of the two). On this occasion it was possible to anchor the sensing head within only a few centimetres of the beach surface. For this reason backwash pressures were well represented on this record (downward deflections on trace (a)). Swash and backwash pressures were also fairly evenly distributed in time and intensity (approximately 0.5-1.0Kg/79cm^2, or 0.6-1.3gm/cm^2.

By 1020hrs (Fig: 7.19B) waves were breaking around the instrument position (Plate 40), although the transducer trace was virtually unchanged in its general appearance from the previous sample. By 1040 hrs (Fig: 7.19C) the tide had risen to a level which covered $\frac{3}{4}$ of the height of the depth guage (1.5m). The pressure trace showed only small amplitude deflections producing swash pressures of > 0.5Kg/79cm^2. However, backwash pressures were distinctly less than this suggesting net landward flow forces were prevailing. At 1132 hrs (Fig: 7.19D), when the depth guage was almost permanently covered, the pressure had picked up slightly. The instrument was now positioned seawards of the breaker line.

By 1200 hrs the tide was receding from the beach ridge. The wave field had become very irregular and was declining in strength. The instrument was only affected by a few swashes producing pressures < 1Kg/79cm^2. The author had noted this tendency for the intensity (amplitude) of wave fields to decline on the ebbing tide on many previous occasions. Figure 7.13L shows that the low energy conditions did little to alter the overall sediment structure of the beach or profile configuration.

7.6.3.5 25th April 1981

Plates 41 and 42 give an impression of the wave conditions prevailing on this date (H_b = 122cms/4', T_b = 7.6 sec). Phase-difference was 0.51 and run-up period was 9.3 sec, suggesting a somewhat irregular wave field. At 911 hrs the waves were breaking in alternately spilling and plunging modes, producing analogue records shown in Figure 7.20A. Whereas the pressure trace showed some mechanically induced zero-shift, that observed in the depth guage trace was probably due to the swift rise in tide which can often be observed over short periods of time. The pressure trace was typical of swash tip conditions when there is little or no recorded backwash. Peak pressures were approximately 2Kg/79cm^2 (2.5gm/cm^2).

By 916 hrs the fast flowing tide had risen to a level at which each consecutive swash affected the sensing head (Fig: 7.20B). The depth guage signal had become unstable and was subsequently switched off. Unavoidable zero-shift persisted in the pressure trace, which now showed signs of backwash flow forces. Swash forces of up to 8Kg/79cm^2 (10.2 gm/cm^2) were recorded, together with backwash forces of approximately 1Kg/79cm^2 (1.3 gm/cm^2) which persisted for up to 5 seconds. The trace for 955 hrs shows even higher levels of swash/backwash flow pressure (Fig: 7.20C). Short duration swashes of up to 6Kg/79cm^2 (7.6 gm/cm^2) were followed by relatively longer duration backwash pressures of up to 3Kg/79cm^2 (3.8 gm/cm^2). The swash pulse at (i) was caused by a plunging wave breaking onto the face of the instrument. That at (ii) was caused by the intense, rotating eddy of a plunging wave, breaking 1m seawards of the instrument. After up-beach flow forces fell with the continued passage of this translatory wave, strong backwash pressures were recorded at (iii).

Before the pressure trace became unreliable at 1105 hrs as a result of water entering the transmission cable, the analogue record shown in Figure 7.20D was obtained. This was badly affected by zero-shift, but nevertheless shows the rapidly fluctuating on-beach/off-beach flow pressures prevailing at around high tide. The period and amplitude of swash and backwash deflections was highly irregular, providing evidence of a highly disturbed water column around the instrument. Some of the peak deflections could have been caused by the material colliding with the sensing head. Rapid changes in the direction of flow pressure, as seen at (i) in Figure 7.20D, appeared related to swashes overriding backwash.

Figure 6.13M shows that the overall result of these wave conditions was 'constructional', with a small mid-beach berm being formed at the swash limit. Little change appeared to have taken place to the surface sediment structure, except for the exposure of a coarse tail trapping some fine elements, at the ridge base. No swash velocity measurement was made on this occasion.

7.6.3.6 9th May 1981

This, and the final experiment, involved the use of the Mark II version of the swash transducer (Fig: 7.8, section 7.4.4). Two pressure channels were now available, the first recording up/down beach (swash/backwash) flow pressures, and the second recording along-beach flow pressures. A swell wave pattern, breaking nearly normal to the shore, produced H_b = 61cms (2') and T_b = 7.7 secs. Phase-difference was in surge condition at 0.40, indicating 'constructional' conditions. There was some cusping around the instrument, which was located on a cusp horn.

Figure 7.21A shows the two analogue pressure tracers at 938 hrs. The upper trace (a) represents along-beach flow forces, with a deflection towards the top of the diagram indicating a flow southeast towards Nash Point. There was little record of backwash forces at this time. Swash forces reached peak values of 3.4Kg (note that because of the disc-shaped sensing head it was no longer possible to approximate pressures to cm^2). Alongshore flow forces were not consistent in direction, and were of the order of 0.3-0.7Kg where they occurred. At (i) a complex swash eddy, causing a momentary change of direction on the lower trace, produced along-shore pressures in both directions. This may have been caused by a particle colliding with the instrument.

As the tide rose, waves pushed material up-beach, almost covering the sensing head at one point (Plate 43). At 1006 hrs, when the tide had covered the instrument, peak swash forces were producing pressures up to 4.7Kg (Fig: 7.21B). Very much smaller amplitude deflections in the opposite direction in trace (b) produced backwash pressures of 0.5Kg. Along-shore flow pressure continued to be small in magnitude and variable in direction. By 1013 hrs (Fig: 7.21C) the wave field had become so irregular that there were only brief phases of significant wave action. Swash forces generally continued to predominate over backwash forces while a small ridge of material continued to be pushed inland. The trace at (i) indicates the rapidly varying directional components of a plunging wave breaking directly onto the instrument. Such variable pressures must be responsible for considerable scour at the wave break point.

Figures 7.21D-E show the pressure records immediately either side of high tide. Periods of wave activity were sporadic and pressures low. Along-beach flow forces were practically non-existant. By 1238 hrs (Fig: 7.21F) the instrument was again under the influence of swash and backwash. On-shore forces were still predominating. As the sea fell below the ridge base, only a few waves were able to reach the sensing head (Fig: 7.21G), although these still produced significant pressures (2Kg). The instrument was left approximately 15 cm further above the beach surface than before the experiment commenced (Plate 44). Figure 7.13N shows how material had been transported from the lower to the upper beach during the tidal cycle.

7.6.3.7 1st June 1981

Low energy wave conditions prevailed on this date (H_b = 30cm/1', T_b = 7.2 sec). Phase-difference was 0.33 so that the swash zone was in 'constructive' surge phase, and a run-up period of 7.3 sec indicated that the degrading swell wave field was of almost perfect regularity. Plate 45 shows how the base plate was exposed towards the base of a 'swell type' profile. The Mark II swash transducer was used exactly as in the previous experiment with the two pressure analogue records. Figure 7.22A shows these records at 1645 hrs, when swash velocity was averaging 3.3 m/sec at the instrument position (Fig: 7.12M). Swash flow pressures at the swash tip were reaching 1.3Kg. There was little evidence of backwash, partly because of the distance between the sensing head and beach surface. Along-shore flow forces were irregular in direction and of insignificant magnitude.

By 1700 hrs wave break point had moved landwards of the instrument and the analogue records (Fig: 7.22B) showed much reduced pressure levels. Plate 46 shows the conditions at this time. Within 10 minutes, pressure levels had fallen still further (Fig: 7.22C) until only the faintest deflections could be associated with the passage of swash and backwash (approximately 6gm). Figure 7.22D shows the output from both channels at four times during the ebbing tide. After high tide, conditions became so calm that there was no evidence of swash, backwash or along-beach flow pressures. Not surprisingly Figure 7.130 indicates that there was barely any alteration to the profile configuration. Despite the calm conditions, however, there was a detectable change to the size composition of sediment at the high tide mark (point B, Fig: 7.130).

7.7 DISCUSSION AND FUTURE OBJECTIVES

In contrast to the swash velocity results, which indicated relatively constant swash edge flow speeds up the beach face, flow pressure records, from the swash transducers, highlighted the extremely variable spatial and temporal nature of swash zone flow structure. It is obvious from these results that a wide variety of physical processes and responses take place throughout the tidal cycle. This means that 'static' pre or post high tide beach parameter samples (under which heading could be lumped all the data used in Chapters 4, 5 and 6 of this thesis), only represent either (1) the net resultant of all these actions, or (2) the final version of a series of contradictory actions.

Although swash transducer results were limited, both in quantity and in the range of physical conditions they covered, it was quite apparent that phase relations played a central role in determining processes operating in the swash zone (Kirk, 1970). Even during the occurrence of a relatively regular wave field, the relationship between swash and backswash at any point, and at any time, appeared to move in and out of phase. This had a most profound effect on the magnitude and direction of flow forces, which in turn determined optimum sediment entrainment or depositional conditions. The great variety of parameters pertaining created an unpredictability in the physical system which gave significance to chance relations between beach and waves.

The problems of developing an adequate instrument system, and embarking, at a late stage in the research programme, on a new and exacting field of investigation, were considerable. For this reason it has been impossible to step beyond a qualitative approach in presenting results. Not only were the pressure data difficult to use in a statistical evaluation (being in analogue form, and confused by zero shift), but beach response information was also difficult to quantify in a form which could have enabled processs/response correlations. Even where a statistical comparison of the 'before' and 'after' sample size distributions was undertaken (top third of Figs: 7.13A-O), no clear pattern emerged between prevailing swash pressures and the incidence of significant results. Further consideration needs to be given to the process/response relations under investigation, as this will determine the way in which the swash transducer is used.

It is clear that, in future, swash transducer data should be used in a more sophisticated analysis of phase relations. Concurrent with this, there should be a more consistent examination of pressure records through time. Ironically, the development of the high resolution swash transducers presented here, made an examination of this kind more complex. The mechanically insensitive instruments of Schiffman (1965) and Kirk (1970) had the advantage of nil zero drift (both had a lower cut-off point of considerable magnitude). This meant that only the relatively large magnitude portion of flow forces operating was actually recorded, and it was correspondingly easier to analyse results in analogue form.

Both the Mark I and Mark II transducers had a response time considerably shorter than that of the chart recorder. Not only did the recorder therefore filter results, but mechanical inertia in the recording pen system influenced the magnitude of trace deflections. These difficulties indicate that a digital read-out, taken at a resolution comparable to the sensing system, is essential. The first step towards this objective was taken during a field experiment on the 17th of December, 1981. Although the digital data transformer worked satisfactorily, problems in the circuit design did not enable these signals to be read coherently from the magnetic tape.

The development of a digital recorder, coupled with the need to dispose of the unsatisfactory transmission cable arrangement, means that the next generation of transducers should incorporate a micro-processor controlled digital recording system 'on board' the sensing equipment. In other words, one or more cassette tape recorders would need to be sealed in a water-tight housing beneath the sensing head. This would then receive continuous, or discrete batches of pressure data in digital form. As a result, computer assisted analysis of flow forces through time, as well as a thorough examination of phase relations throughout the tidal cycle, could be reasonably contemplated.

However, this redesigned instrument system would give rise to other logistical considerations in its application, which would be central to the quality and relevance of results obtained. It is clear that the position of the sensing head, with respect to the beach surface, is of paramount importance in determining the pertinence with which data may be used in an analysis of depositional conditions. The design and emplacement of a beach anchoring system capable of bringing the sensing head into contact with the beach surface, is a problem of no lesser scientific significance than is that of developing the instrument system itself. With the head in this position, and using a digital recording system connected to a combination of strain guages (Fig: 7.10), it should be possible to distinguish between water particle flow pressures, and extreme forces arising from sediment contact with the instrument. Such a possibility could provide evidence against which physical models, such as Bagnold's (1968) 'dispersive stress theory', could be tested.

Finally, any research programme is always restricted in terms of resources and logistical support. In the correct circumstances it should be possible to continue the development of the Mark I version swash transducer. However, in more restricted circumstances, the Mark II version promises greater short-term advance in swash zone studies. The advantage of interchangable sensing heads opens the door to advanced mathematical modelling of particle entrainment forces, and controlled hydraulic engineering studies. The application of such work to a further investigation of natural conditions should offer a fuller understanding of beach processes. It is at the micro-level of spot sampling, made possible by swash transducers, that the macro-level structure of beaches and their sediments, might be better explained.

7.8 SUMMARY

Previous work on nearshore wave mechanics has been noted. A review of the major physical properties of the swash zone included consideration of wave asymmetry, phase relations, turbulent flow and particle entrainment processes. The role played by beach water table level, and the velocity characteristics of the leading swash edge, have also received attention.

Details of Kirk's (1970) instrument system for measuring swash zone processes have been provided, with particular reference to its practical shortcomings. Two new prototype systems, each based on different physical principles, have been described, and their designs justified in practical terms. In addition, specifications have been given of a wave height recorder (depth guage), and a procedure outlined for measuring swash velocity. Some of the problems associated with the application of these instruments to swash zone process measurement have been compiled.

Results of 13 swash velocity experiments have been presented and analysed. Data produced no evidence of appreciable velocity variation either spatially across the beach profile, or over time. Instead, results indicated that velocities were reasonably constant throughout most of the passage of incoming swash, with rapid deceleration limited to a short distance behind the limit of swash run-up. This distance, being generally shorter than the average distance between marker rods meant that velocity data taken near run-up limit was inherently more variable in magnitude than at points closer to the breaker zone.

Six experiments involving the use of swash transducers, in association with swash velocity and depth guage measurements, have been individually described. Data, in the form of analogue chart records, provided evidence of extremely variable physical processes operating throughout the tidal cycle. Some of these have been described in terms of the magnitude and direction of flow forces over time, for individual waves. Such information underlined the limitation of 'static' beach parameter samples.

These preliminary results have pointed the way to further research. Consideration has been given to some useful modifications which could and should be made to the basic swash transducer system. In particular, a digital recording system located 'on board' the sensing equipment should be developed, together with a mechanical device which could manoeuvre the sensing head so that it is in contact with the beach surface. It has been argued that such advances could offer the best means of understanding the vicissitudes of beach structure and sediment.

CHAPTER 8

CONCLUSIONS

"I remember when in Good Success Bay, in Tierra del Fuego, thinking that I could not employ my life better than in adding a little to natural science. This I have done to the best of my abitities and critics may say what they like, but they cannot destroy this conviction...."

Charles Darwin, in "The Voyage of Charles Darwin", BBC Publications, London.

8.1 INTRODUCTION

The foregoing comprehensive examination of aspects of two pebble beaches has dealt with (1) the depositional characteristics of individual beach particles and their relationship with background beach material, (2) the analytical modelling of beach morphology, and the relationship between this and wave process conditions, (3) the sedimentary characteristics of the surfaces of both beaches, and the identification of justifiable sub-facies zonational arrangements, and (4) the development and initial results of swash-zone flow structure measurement apparatus, from which further key research has been proposed.

Each of these areas of study has highlighted the distinct nature of coarse clastic beaches. As a result, an approach which is both methodologically and analytically different from that adopted by those investigating sand beach phenomenae, is required. Each of the four areas of study listed above has also produced significant insights into the behaviour of coarse clastic beaches under a variety of conditions, some of which have led to new conceptual models or a valuable reappraisal of ideas proposed by other workers in this field. A summary of pertinent conclusions is given as follows:

8.2 TRACER STUDY

This produced evidence that particle thickness (C-axis) was the most susceptible parameter to swash/backwash movement. This probably results from the fact that particles generally tend to settle out of liquids with their maximum projection surfaces horizontal, resisting downward motion. They then present their A x C or B x C planes (or any intermediary between these two) to the initial moment force of the swash or backwash. Pebble thickness is therefore an important factor in determining threshold entrainment conditions. This is a conclusion which corroborates the work of Carr (1974). Despite the fact that linear regression results only accounted for around 4% of the down-beach and along-beach tracer distributions, particle C-axis was found time and again to produce significant relationships with tracer distributions. It is clear that these relationships were complicated by such factors as particle imbrication, beach slope angle, non-linear trends, and inevitable sampling error.

Results also showed that tracers possessing relatively larger C-axes travelled relatively further along-beach and down-beach from the injection point. This relationship was probably not well expressed in linear terms because of the compex interconnection between tracers and background beach material. Results also indicated that shape-sorting processes were rather weakly expressed on Gileston beach; there being only five significant rearrangements of the tracer distribution over 14 months. A possible sorting model for this beach would make along-shore differential movement/sorting a secondary response to down-beach selective sorting mechanisms. This stems from the fact that sea waves are only active over the basal portion of the beach during a large period of the spring-neap-spring tidal cycle, which means that pebbles in this vicinity (thicker, spherical particles) are able to make relatively greater progress along the beach under the influence of longshore forces.

An original analysis of the relationship between tracers and the background beach population revealed considerable dissimilarity between (1) 'returned tracer populations' and the original population of tracers, and (2) individual tracers located on the beach surface, and material with which they were in immediate contact (their 'host populations'). Using ideas first developed by Moss (1962, 1963), a modified model of sediment deposition beneath sea waves has been proposed to explain (1) and (2) above. When applying Moss's (1962, 1963) sedimentation model to the behaviour of tracer particles on a natural beach surface, indigenous beach material constitutes the initially deposited sediment (Moss's 'A' population). As swash and backwash rythmically disturbs the topmost beach layers they would create a 'traction carpet'. Processes which sort the material each time this traction carpet is created, would either maintain, reinforce or reassemble its initial sedimentological composition.

As this process takes place some tracers might become selectively incorporated in the sediment, while others remained in motion in the traction carpet. Those which became incorporated would then become characteristic of the sediment, whereas those 'rejected' and remaining in motion would only come to rest on the beach surface if, and when, they settled out of the water between each translatory wave. A schematic picture of this selective process is contained in Figure 4.12 (Caldwell, 1981). If this model is correct it helps explain why tracers found on the beach surface were those dissimilar to the background beach material, because those which were similar would have been distributed throughout the whole layer of beach last subjected to disturbance by waves.

8.3 BEACH MORPHOLOGY

Beach profile configuration has particular significance as a facies attribute on coarse clastic beaches. This parameter displays stochastic control and provides information which is part of a non-stationary Markovian process because configuration is partly a function of the preceeding profile. Using Sonu and Van Beek's (1971) approach (initially developed for a micro-tidal sand beach environment) a successful classification system has been proposed for pebble beach morphological investigations. A number of refinements have been made to the original model of Sonu and Van Beek (1971), which should enable more widespread use to be made of its potential. These are:

1. Angular standardisation of profiles which overcomes problems caused by variation in profile height and width. This enables a more accurate visual classification to be made.
2. Adaptation of the concepts of hypsographic curves

and integrals to beach profile study. The integral can be used to represent a one-dimensional description of profile configuration, and always lies between 0 and 1.

3. Derivation of a 10 category classification system of particular relevance to the study of coarse clastic beaches.
4. Statistical proof that not only the profile macro-form (concave, linear, convex), but also the existence or non-existence of a berm can be distinguished by adopting the integral approach.

Four investigations of profile configuration highlighted the spatial and temporal variety in form that can be observed under apparently similar littoral conditions. This suggested some insufficiency in using a two dimensional profile approach in facies modelling. However, some morphological patterns were discernable which could form the basis for amended or refined models of pebble beach sedimentation.

Throughout the investigation, differences between sand and pebble beaches were noted. Key differences can be summarised as follows:

1. The relatively larger particle size on pebble beaches reduces the role of surface tension and interpore water

retention. This in turn reduces water-table lag time and enhances the constructive power of the swash.

2. The relatively steeper beach face angles found on pebble beaches arising from the above characteristics.
3. The predominance of concave macro-forms on pebble beaches (crest to base), with linear forms confined to the lower beach portion.
4. The relatively smaller width of fringing pebble beaches which do not extend below low water level. This can influence the development of certain types of morphology.
5. Because fringing pebble beaches have a restricted width, changes in morphology cannot necessarily be ascribed to absolute variations in sediment storage, as seen in offshore/ onshore sediment transport on sandy beaches. Instead, longshore redistribution of accumulations of material is a more realistic explanation for pebble beaches.

8.4 BEACH SEDIMENTOLOGY

A large quantity of sedimentological data derived from two types of sampling routine has provided evidence of size and shape relationships, as well as indicating the probable origins of both study beaches. Sediment samples from both beaches displayed a rough balance between discs and spheres (using Zingg's 1935 classification), which together made up over two thirds of all particle shapes. The ratio of discs against spheres proved a vital factor in the description of different sediment types.

In contrast to Bluck's (1967) observations on adjacent beaches, evidence of significant along-beach variations in sediment composition was observed. This was proved statistically and in terms of size/shape relationships. Both these indicated the importance of longshore drift on Nash beach in particular. Such compositional variation could most commonly be seen on both beaches in relation to particle size and size sorting.

Down-beach changes in sediment type were of approximately the same magnitude as along-beach variation on Gileston beach, whereas at Nash these changes were of secondary importance. Size/shape relationships using the C-axis to represent size, produced results quite contrary to those presented as criteria for zonational division by Bluck (1967). It was apparent that the choice of size parameters was influencing results, and subsequent recalculation using both A and B-axes produced significantly different size/shape arrangements.

It has been shown that each axis, when used in the graphical size/shape procedure, creates its own tendency to realise greater proportions of shapes at different points under the size-frequency curve. It is therefore necessary to follow Bluck's (1967) preference for the B-axis to obtain results indicative of his proposed zones. Bluck's (1967) emphasis on the role of backwash in shape sorting is held responsible for the derivation of a one-sided sedimentation system. Reliance upon B-axis results, with their distinct size/shape tendencies appears to have led Bluck (1967) to reject particle mass (size) as a factor in determining a particle's transportational and depositional potential. It has therefore been proposed that shape sorting, while an important process, is not necessarily the primary one responsible for pebble beach facies response.

It is suggested that on the beaches studied, where particle sizes vary considerably (with a range of over 10^4 cm^3), that at times only certain sizes are genuinely active within the prevailing traction carpet. Among those which are active, shape selection under certain conditions plays an important part in bringing shapes with a high pivotability (rods and spheres) down towards the beach toe, while forcing oblate shapes (blades and discs) up the beach face. These processes may be more effective under mid to low energy conditions when winnowing action below the breaking wave and in backwash might loosen spherical and prolate material, allowing gravitational forces to assist its seaward transport. Coincident with this, turbulence of plunging breakers and in the leading swash edge, might facilitate oblate particle entrainment, throwing such material landwards. Under these 'constructional' conditions berm related disc imbrication and lower beach prolate/spherical infill should be enhanced in active particle sizes.

At higher wave energies (storm conditions) particle mass, rather than shape, might play a more important part in swash/backwash entrainment. Spherical and prolate material (along with oblate) might be flung landwards in the turbulent swash edge, while equally less shape-discerning undertow forces, associated with the high phase-differences of short period storm waves, might pull material down-beach for incorporation into the storm bar. Naturally, zonational division between oblate and prolate/spherical materials, established under lower energy conditions, would have an influence on the material available to entrainment processes at any point. Thus a predominance of blades and discs around the beach crest would ensure the prospects of these shapes being realised in beach storm facies, albeit mixed more generally with other shapes. On the same basis, a predominance of prolate/spherical material at lower beach positions would ensure their strong representation in storm bar facies. But particle size rather than shape would determine entrainment potential and transport rates during high energy or storm conditions, making the beach less clearly zonational in structure. This energy controlled balance between the primacy of particle shape and size has latterly been recognized by Carr (pers. comm., 1982). Eight distinct depositional types of sediment were selected as a means of identifying specific sub-facies. Using the size/shape methodology, shape selection was associated with the deposition and erosion of berms. Disc-rich deposits can take a constructional form when laid down at the crest of a berm, or be formed as a lag sediment during the erosion of top-beach material. The arrangement of sediment on the lower beach appears more complex, although spherical and prolate particles were more commonly realised in material infilling the frame of cobbles and boulders at this position. Attempts to link the derivation of these depositional types with generalised environmental conditions proved fruitless.

By concentrated and systematic sampling of a small area of beach face it was possible to appreciate the scale of sediment variation. It was just possible to generalise process/response conditions from environmental data. This work underlined the need for a means of accurately measuring swash zone processes, because refraction-controlled, along-beach variation in wave energy levels complicatedpredictionsabout faciesresponse.

Models for the genesis of Gileston and Nash beaches have been proposed. Both started from the same initial onshore migration of loose shelf sediment, upon which size and shape sorting was etched. The ridge from which the present day beach at Gileston is built, was able to roll onshore unimpeded, responding at all times to the influence of high wave energy conditions. It has subsequently evolved a stable relationship with the presently prevailing wave energy regime. Marginal entrainment conditions are more commonly encountered on this beach which consequently displays evidence of shape sorted deposits.

In contrast, the ridge of sediment which was to form the beach at Nash, came into contact with an old cliff line at a certain point during its post-glacial history, which impeded further migration. From this time onwards the beach became modified by increasing wave energy conditions, and a supply of fresh sediment from its landward margin. Longshore breakdown and transport of material from the central beach area towards its eastern end has partly over-ridden down-beach shape sorting processes. Entrainment forces are such that the shape transition down-beach is more gradual here than at Gileston, while along-beach size sorting takes precedence.

8.5 BEACH HYDROLOGY

In response to the need for direct swash zone wave parameter data to replace more generalised descriptions of littoral conditions, two new prototype instruments, each based on different physical principles, were built and field tested on Nash beach. Information has also been provided about a wave height recorder (depth gauge), and a procedure for measuring swash velocity on a steep pebble beach. Since a considerable amount of work was undertaken field testing the instrument system in one of the most rugged of littoral environments, some of the problems associated with the application of swash zone instrumentation have been detailed.

Results of 13 swash velocity experiments produced no evidence of appreciable velocity variation either spatially across the profile, or over time. Instead, results indicated that velocities were reasonably constant throughout most of the passage of incoming swash, with rapid deceleration limited to a short distance behind the limit of swash run-up. Six experiments involving the use of swash transducers have been individually described. Data, in the form of analogue chart records, provided evidence of extremely variable physical processes operating throughout the tidal cycle. Some of these were described in terms of the magnitude and directon of flow forces over time, for individual waves. Such information underlined the limitation of 'static' beach parameter samples.

These were only preliminary results, and it is clear that swash transducers have yet to be applied to their full potential. Details have been given of some useful modifications to the instrument system, which might make this possible. In particular, a digital recording system located 'on board' the sensing equipment should be developed. Data could then be used in a computer assisted analysis of flow forces through time, as well as a thorough examination of phase relations which clearly play a central role in determining processes operating in the swash zone. The position of the sensing head is of crucial importance when using swash transducers. With the head in close contact with the beach surface, and using a digital recording system with the same response period as the instrument itself, it should be possible to distinguish between water particle flow pressures, and extreme forces arising from sediment contact with the instrument. Such a possibility could provide evidence against which physical models of particle entrainment and deposition could be tested.

8.6. POST SCRIPTUS

As a contribution to the study of pebble beach sedimentation, this research has hopefully done something to proclaim the subject's relevance to an overall understanding of present day littoral processes. There seem to have been relatively few such comprehensive studies, although a handful of mainly European investigators have published a valuable series of papers over the last two decades. Coarse clastic beaches are undoubtedly one of nature's finest engineering structures, acting as a highly responsive buffer between land and sea. This property has long been recognised, if only implicitly, by civil engineers concerned with coastal work. Although pebble beaches are largely restricted to temperate latitudes of the northern and southern hemispheres, they are often extensively developed. A fuller understanding of their genesis, behaviour and protective qualities would therefore seem a sensible objective for the inhabitants of these parts. This implies further investigation, not only of special features such as spits or tombolas, but also of the structural properties of commonly developed fringing pebble beaches.

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